Bringing Astrophysics and Cosmology to the Particle Data Book

PDG: 60 years of evaluating data

M. Barnett – May 17, 2017

1996 PDG Meeting

M. Barnett – May 17, 2017

2000 PDG Meeting

M. Barnett – May 17, 2017

Keith became a PDG author

with the 1986 edition

16 editions (32 years).

Minnesota note:

Serge Rudaz and Tony Gherghetta

have also been PDG authors.

Because of his outstanding service, Keith was made first author of the 2014 edition.

pdgLive | Summary Tables | Reviews, Tables, Plots | Particle Listings

HOME:

Authors
of the 2014 edition.

K.A. Olive *et al.* (Particle Data Group), Chin. Phys. C, **38**, 090001 (2014).

AUTHORS:

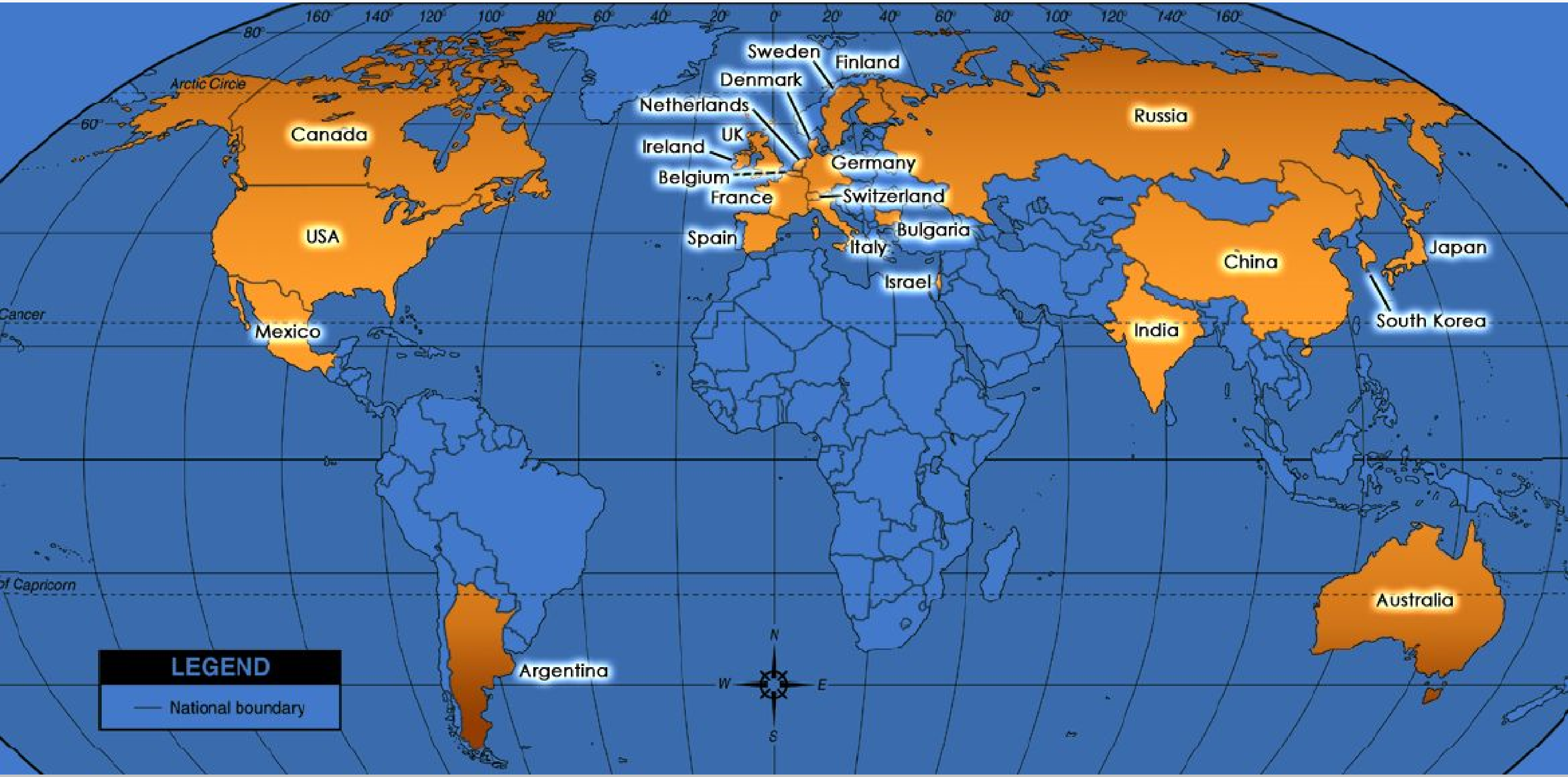
K.A. Olive, [1] K. Agashe, [2] C. Amsler, [3] M. Antonelli, [4] J.-F. Arguin, [5] D.M. Asner, [6] H. Baer, [7] H.R. Band, [8] R.M. Barnett, [9] T. Basaglia, [10] C.W. Bauer, [9] J.J. Beatty, [11] V.I. Belousov, [12] J. Beringer, [9] G. Bernardi, [13] S. Bethke, [14] H. Bichsel, [15] O. Biebel, [16] E. Blucher, [17] S. Blusk, [18]

Before more about Keith:

What is PDG?

PDG Collaboration

223 authors from 148 institutions 24 countries
plus 700 consultants



Author Lists

1988

REVIEW OF PARTICLE PROPERTIES

Particle Data Group

G.P. Yost, R.M. Barnett, I. Hinchliffe, G.R. Lynch, A. Rittenberg, R.R. Ross, M. Suzuki, T.G. Trippe, and C.G. Wohl
Technical Associates: B. Armstrong and G.S. Wagman
Lawrence Berkeley Laboratory,[†] University of California, Berkeley, CA 94720, USA

F.C. Porter
Department of Physics, California Institute of Technology, Pasadena, CA 91125, USA

L. Montanet
CERN, European Laboratory for Particle Physics, CH-1211 Geneva 23, Switzerland

M. Aguilar-Benitez and J.J. Hernandez[‡]
C.I.E.M.A.T., E-28040, Madrid, Spain,
and CERN, European Laboratory for Particle Physics, CH-1211 Geneva 23, Switzerland

G. Conforto
Istituto Nazionale di Fisica Nucleare, Sezione di Firenze, I-50125 Firenze, Italy

R.L. Crawford
Department of Physics and Astronomy, University of Glasgow, G12 8QQ Glasgow, Scotland

K.R. Schubert
Institut für Hochenergiephysik, University of Heidelberg, D-69 Heidelberg, Federal Republic of G
and CERN, European Laboratory for Particle Physics, CH-1211 Geneva 23, Switzerland

M. Roos
Department of High Energy Physics, University of Helsinki, SF-00170 Helsinki 17, Finland,
and Istituto Nazionale di Fisica Nucleare, Sezione di Firenze, I-50125 Firenze, Italy

N.A. Törnqvist
Department of High Energy Physics, University of Helsinki, SF-00170 Helsinki 17, Finland

G. Höhler
Institut für Theoretische Kernphysik, University of Karlsruhe, D-7500 Karlsruhe 1, Federal Repu

K. Hagiwara and S. Kawabata
KEK, National Laboratory for High Energy Physics, Oho-machi, Tsukuba-gun, Ibaraki-ken 305,

D.M. Manley
Department of Physics, Kent State University, Kent, OH 44242, USA

K.A. Olive
School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA

K.G. Hayes and R.H. Schindler
Stanford Linear Accelerator Center, Stanford, CA 94305, USA

B. Cabrera
Department of Physics, Stanford University, Stanford, CA 94305, USA

R.E. Shrock
Department of Physics, State University of New York, Stony Brook, NY 11794, USA

R.A. Eichler
IMP of ETH-Zürich, CH-5234 Villigen, Switzerland

L.D. Roper and W.P. Trower
Department of Physics, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA

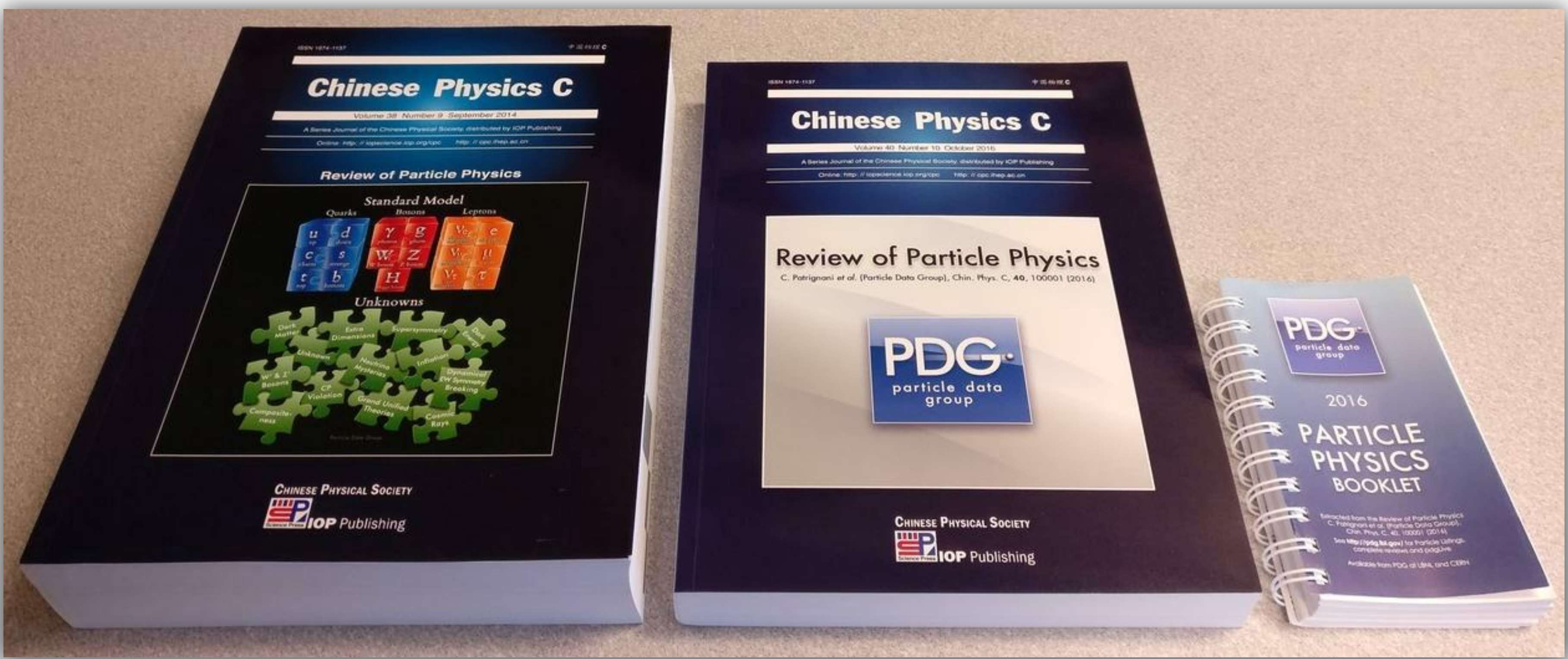
C. Patrignani *et al.* (Particle Data Group), Chinese Physics C, 40, 100001 (2016) 1

2016

Particle Data Group

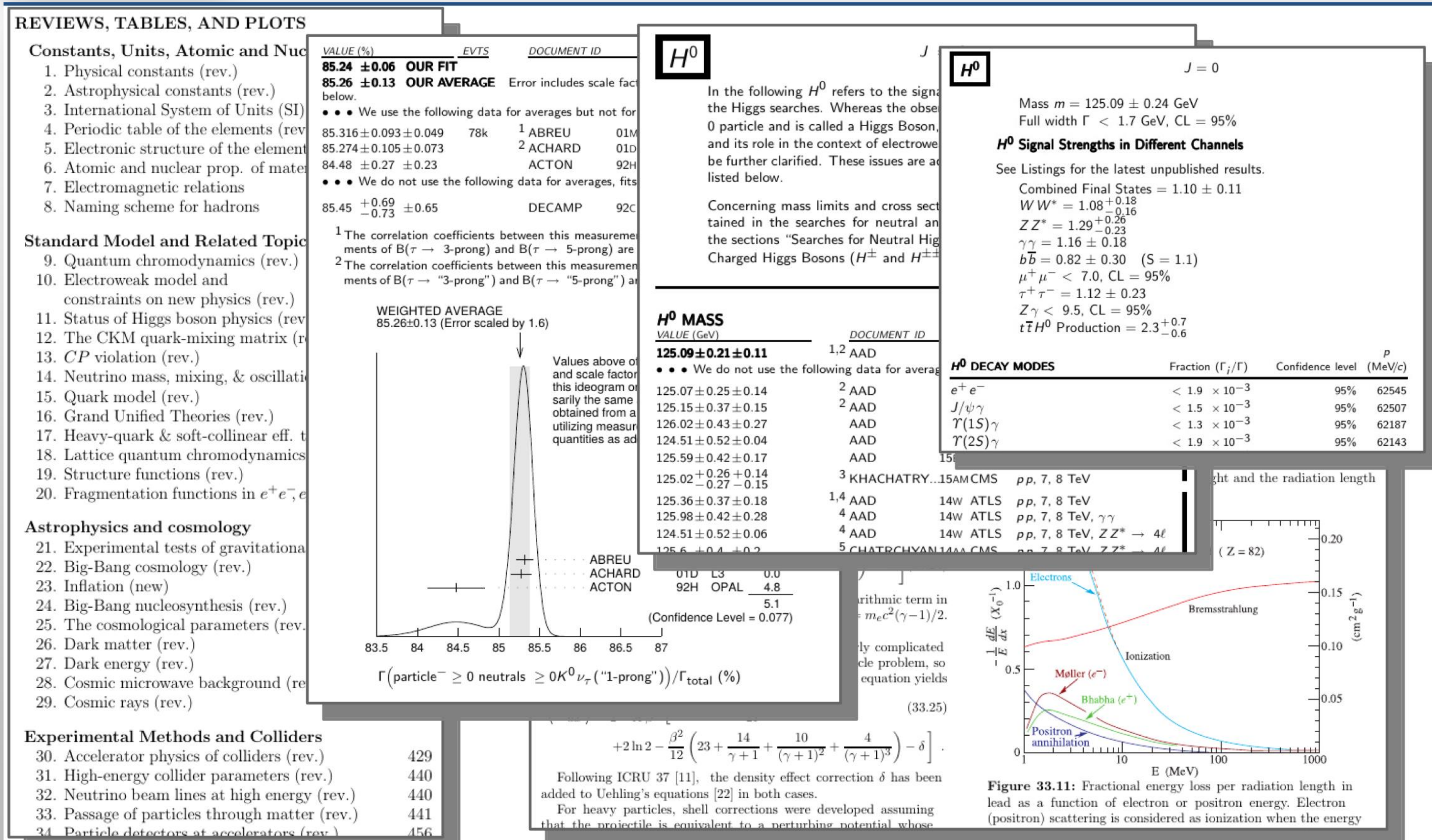
C. Patrignani,[1] K. Agashe,[2] G. Aielli,[3] C. Amsler,[4,5] M. Antonelli,[6] D.M. Asner,[7] H. Baer,[8] Sw. Banerjee,[9] R.M. Barnett,[10] T. Basaglia,[11] C.W. Bauer,[10] J.J. Beatty,[12] V.I. Belousov,[13] J. Beringer,[10] S. Bethke,[14] H. Bichsel,[15] O. Biebel,[16] E. Blucher,[17] G. Brooijmans,[18] O. Buchmueller,[19] V. Burkert,[20] M.A. Bychkov,[21] R.N. Cahn,[10] M. Carena,[22,17,23] A. Ceccucci,[11] A. Cerri,[24] D. Chakraborty,[25] M.-C. Chen,[26] R.S. Chivukula,[27] K. Copic,[10] G. Cowan,[28] O. Dahl,[10] G. D'Ambrosio,[29] T. Damour,[30] D. de Florian,[31] A. de Gouvêa,[32] T. DeGrand,[33] P. de Jong,[34] G. Dissertori,[35] B.A. Dobrescu,[22] M. D'Onofrio,[36] M. Doser,[11] M. Drees,[37] H.K. Dreiner,[37] D.A. Dwyer,[10] P. Eerola,[38,39] S. Eidelman,[40,41] J. Ellis,[42,11] J. Erler,[43] V.V. Ezhela,[13,44] W. Fetscher,[35] B.D. Fields,[45,46] B. Foster,[47,48,49] A. Freitas,[50] H. Gallagher,[51] L. Garren,[22] H.-J. Gerber,[35] G. Gerbier,[52] T. Gershon,[53] T. Gherghetta,[54] A.A. Godizov,[13] M. Goodman,[55] C. Grab,[35] A.V. Gritsan,[56] C. Grojean,[57] D.E. Groom,[10] M. Grünewald,[58] A. Gurtu,[59,11] T. Gutsche,[60] H.E. Haber,[61] K. Hagiwara,[62] C. Hanhart,[63] S. Hashimoto,[62] Y. Hayato,[64] K.G. Hayes,[65] A. Hebecker,[66] B. Heltsley,[67] J.J. Hernández-Rey,[68] K. Hikasa,[69] J. Hisano,[70] A. Höcker,[11] J. Holder,[71,72] A. Holtkamp,[11] J. Huston,[27] T. Hyodo,[73] K.D. Irwin,[74,75] J.D. Jackson,[10†] K.F. Johnson,[76] M. Kado,[77,11] M. Karliner,[78] U.F. Katz,[79] S.R. Klein,[80] E. Klempt,[81] R.V. Kowalewski,[82] F. Krauss,[83] M. Kreps,[53] B. Krusche,[84] Yu.V. Kuyanov,[13] Y. Kwon,[85] O. Lahav,[86] J. Laiho,[87] P. Langacker,[88] A. Liddle,[89] Z. Ligeti,[10] C.-J. Lin,[10] C. Lippmann,[90] T.M. Liss,[91] L. Littenberg,[92] K.S. Lugovsky,[10,13] S.B. Lugovsky,[13] A. Lusiani,[93] Y. Makida,[62] F. Maltoni,[94] T. Mannel,[95] A.V. Manohar,[96] W.J. Marciano,[92] A.D. Martin,[83] A. Masoni,[97] J. Matthews,[98] U.-G. Meißner,[81,63] D. Milstead,[99] R.E. Mitchell,[100] P. Molaro,[101] K. Mönig,[102] F. Moortgat,[11] M.J. Mortonson,[103,10] H. Murayama,[104,105,10] K. Nakamura,[104,62] M. Narain,[106] P. Nason,[107] S. Navas,[108] M. Neubert,[109] P. Nevski,[92] Y. Nir,[110] K.A. Olive,[54] S. Pagan Griso,[10] J. Parsons,[18] J.A. Peacock,[89] M. Pennington,[20] S.T. Petcov,[111,104,112] V.A. Petrov,[13] A. Piepke,[113] A. Pomarol,[114] A. Quadt,[115] S. Raby,[12] J. Rademacker,[116] G. Raffelt,[117] B.N. Ratcliff,[75] P. Richardson,[83] A. Ringwald,[48] S. Roesler,[11] S. Rolli,[118] A. Romaniouk,[119] L.J. Rosenberg,[15] J.L. Rosner,[17] G. Rybka,[15] R.A. Ryutin,[13] C.T. Sachrajda,[120] Y. Sakai,[62] G.P. Salam,[11,121] S. Sarkar,[122,123] F. Sauli,[11] O. Schneider,[124] K. Scholberg,[125] A.J. Schwartz,[126] D. Scott,[127] V. Sharma,[96] S.R. Sharpe,[15] T. Shutt,[75] M. Silari,[11] T. Sjöstrand,[128] P. Skands,[129] T. Skwarnicki,[87] J.G. Smith,[33] G.F. Smoot,[130,105,10] S. Spanier,[131] H. Spieler,[10] C. Spiering,[102] A. Stahl,[132] S.L. Stone,[87] Y. Sumino,[69] T. Sumiyoshi,[133] M.J. Syphers,[25,22] F. Takahashi,[69] M. Tanabashi,[70] K. Terashi,[64] J. Terning,[134] R.S. Thorne,[86] L. Tiator,[135] M. Titov,[52] N.P. Tkachenko,[13] N.A. Törnqvist,[39] D. Tovey,[136] G. Valencia,[129] R. Van de Water,[22] N. Varelas,[137] G. Venanzoni,[6] M.G. Vincter,[138] P. Vogel,[139] A. Vogt,[140] S.P. Wakely,[17,23] W. Walkowiak,[95] C.W. Walter,[125] D. Wands,[141] D.R. Ward,[142] M.O. Wascko,[19] G. Weiglein,[48] D.H. Weinberg,[143] E.J. Weinberg,[18] M. White,[105,10] L.R. Wiencke,[144] S. Willocq,[145] C.G. Wohl,[10] L. Wolfenstein,[146†] J. Womersley,[147] C.L. Woody,[92] R.L. Workman,[148] W.-M. Yao,[10] G.P. Zeller,[22] O.V. Zenin,[13,44] R.-Y. Zhu,[149] F. Zimmermann,[11] P.A. Zyla[10]

PDG Books



2014 with Data Listings **2016 Data Listings online only** **Booklet**

Content in 2017



M. Barnett – May 17, 2017

Full Summary Table 1957

(from Wallet Cards)

Barkas and Rosenfeld UCRL-8030 Table I

Masses and mean lives of elementary particles; November, 1957
(The antiparticles are assumed to have the same spins, masses, and mean lives as the particles listed)

	Particle	Spin	Mass (Errors represent standard deviation) (Mev)		Mass difference (Mev)		Mean life (sec)		Decay rate (number per second)
Photon	γ	1	0				stable		0
Leptons	ν	$\frac{1}{2}$	0				stable		0
	e^-	$\frac{1}{2}$	0.510976	(a)			stable		0
	μ^-	$\frac{1}{2}$	105.70 ± 0.06	(a)			$(2.22 \pm 0.02) \times 10^{-6}$		0.45×10^{6}
Mesons	π^+	0	139.63 ± 0.06	(a)	4.6 (a)		$(2.56 \pm 0.05) \times 10^{-8}$	(a)	0.39×10^{8}
	π^0	0	135.04 ± 0.16	(a)			$< 4 \times 10^{-16}$	(d)	$> 2.5 \times 10^{15}$
	K^+	0	494.0 ± 0.2	(g)	0.4 ± 1.8		$(1.224 \pm 0.013) \times 10^{-8}$	(h)	0.815×10^{8}
	K^0	0	494.4 ± 1.8	(i)		K_1:	$(0.95 \pm 0.08) \times 10^{-10}$	(e)	1.05×10^{10}
						K_2:	$(4 < \tau < 13) \times 10^{-8}$	(c)	$(0.07 < \tau < 0.25) \times 10^{8}$
Baryons	p	$\frac{1}{2}$	938.213 ± 0.01	(a)			stable		0.0
	n	$\frac{1}{2}$	939.506 ± 0.01	(a)			$(1.04 \pm 0.13) \times 10^{+3}$	(a)	0.96×10^{-3}
	Λ	$\frac{1}{2}$	1115.2 ± 0.14	(j)			$(2.77 \pm 0.15) \times 10^{-10}$	(k)	0.36×10^{10}
	Σ^+	$\frac{1}{2}$	1189.4 ± 0.25	(l)	7.1 ± 0.4		$(0.83 {}^{+.06}_{-.05}) \times 10^{-10}$	(m)	1.21×10^{10}
	Σ^-	$\frac{1}{2}$	1196.5 ± 0.5	(n)	$6.0^{+1.4}_{-0.9}$		$(1.67 \pm 0.17) \times 10^{-10}$	(o)	0.60×10^{10}
	Σ^0	$\frac{1}{2}$	$1190.5^{+0.9}_{-1.4}$	(p)			$(< 0.1) \times 10^{-10}$ theoretically $\sim 10^{-19}$	(b)	$> 10 \times 10^{10}$ theoretically $\sim 10^{19}$
	Ξ^-	?	1320.4 ± 2.2	(q)			$(4.6 < \tau < 200) \times 10^{-10}$	(f)	$(> 0.005, < 0.2) \times 10^{10}$
	Ξ^0	?	?				?		

Wallet Cards 1957

Front ⟷ Back

Barkas and Rosenfeld UCRL-8030 Table I

Masses and mean lives of elementary particles; November, 1957
(The antiparticles are assumed to have the same spins, masses, and mean lives as the particles listed)

	Particle	Spin	Mass (Errors represent standard deviation) (Mev)	Mass difference (Mev)	Mean life (sec)	Decay rate (number per second)
Photon	γ	1	0		stable	0
Leptons	ν	½	0		stable	0
	e^-	½	0.510976 (a)		stable	0
	μ^-	½	105.70 ±0.06 (a)		(2.22 ±0.02) $\times 10^{-6}$	0.45 $\times 10^6$
Mesons	π^+	0	139.63 ±0.06 (a)	4.6 (a)	(2.56 ±0.05) $\times 10^{-8}$ (a)	0.39 $\times 10^8$
	π^0	0	135.04 ±0.16 (a)		< 4 $\times 10^{-16}$ (d)	> 2.5 $\times 10^{15}$
	K^+	0	494.0 ±0.2 (g)	0.4±1.8	(1.224±0.013) $\times 10^{-8}$ (h)	0.815 $\times 10^8$
	K^0	0	494.4 ±1.8 (i)		K_1: (0.95 ±0.08) $\times 10^{-10}$ (e)	1.05 $\times 10^{10}$
					K_2: (4< τ <13) $\times 10^{-8}$ (c)	(0.07< τ <0.25)$\times 10^8$
Baryons	p	½	938.213 ±0.01 (a)		stable	0.0
	n	½	939.506 ±0.01 (a)		(1.04 ±0.13) $\times 10^{+3}$ (a)	0.96 $\times 10^{-3}$
	Λ	½	1115.2 ±0.14 (j)		(2.77 ±0.15) $\times 10^{-10}$ (k)	0.36 $\times 10^{10}$
	Σ^+	½	1189.4 ±0.25 (l)	7.1 ± 0.4	(0.83 $^{+.06}_{-.05}$) $\times 10^{-10}$ (m)	1.21 $\times 10^{10}$
	Σ^-	½	1196.5 ±0.5 (n)		(1.67 ±0.17) $\times 10^{-10}$ (o)	0.60 $\times 10^{10}$
	Σ^0	½	1190.5 $^{+0.9}_{-1.4}$ (p)	$6.0^{+1.4}_{-0.9}$	(<0.1) $\times 10^{-10}$ (b) theoretically ~10^{-19}	>10 $\times 10^{10}$ theoretically ~10^{19}
	Ξ^-	?	1320.4 ±2.2 (q)		(4.6< τ <200) $\times 10^{-10}$ (f)	(>0.005, <0.2) $\times 10^{10}$
	Ξ^0	?	?		?	

Summary Table

Table IV

Atomic and nuclear constants in units of Mev, cm, and sec[a]

GENERAL ATOMIC CONSTANTS

N = 6.0249 $\times 10^{23}$ molecules/gram
c = 2.99793 $\times 10^{10}$ cm/sec
e = 4.80286 $\times 10^{-10}$ esu = 1.6021$\times 10^{-19}$ coulomb.
1 Mev = 1.6021 $\times 10^{-6}$ erg [1 ev = e(10^8/c)]
ℏ = 6.5817 $\times 10^{-22}$ Mev sec = 1.054 $\times 10^{-27}$ erg sec.
ℏc = 1.9732 $\times 10^{-11}$ Mev cm [= ƛ for p = 1Mev/c]
k = 8.6167 $\times 10^{-11}$ Mev/°C [Boltzmann constant]
$\alpha = \frac{e^2}{\hbar c}$ = 1/137.037; e^2 = 1.44$\times 10^{-13}$ Mev cm

Magnetic Moment and Cyclotron Angular Frequency

$\mu_{Bohr} = \frac{e\hbar}{2mc}$ = 0.57883 $\times 10^{-14}$ Mev/gauss
$\frac{1}{2}\omega_{cyclotron} = \frac{e}{2mc}$ = 8.7945 $\times 10^6$ rad sec^{-1}/gauss
$g_{electron} = 2[1 + \frac{\alpha}{2\pi} + 0.328(\frac{\alpha}{\pi})^2] = 2[1.001163]^b$
$g_{muon} = 2[1 + \frac{\alpha}{2\pi} + 0.75(\frac{\alpha}{\pi})^2] = 2[1.001172]^b$

QUANTITIES DERIVED FROM THE PROTON MASS, m_p

Rest mass = 938.211 Mev/c^2 = 1836.12 m_e = 6.719 m_π
= 1.007593 m_1(m_1 = 1 amu = $\frac{1}{16}$ O^{16})

Magnetic Moment and Cyclotron Angular Frequency

$\mu_p = \frac{e\hbar}{2m_pc}$ = 3.1524 $\times 10^{-18}$ Mev/gauss
$\frac{1}{2}\omega_{cyclotron} = \frac{e}{2m_pc}$ = 4.7896 $\times 10^3$ rad sec^{-1}/gauss
$g_p = \left(\frac{\mu}{\mu_p}\right)_{proton}$ = 2.79275; $g_n = \left(\frac{\mu}{\mu_p}\right)_{neutron}$ = −1.9128

QUANTITIES DERIVED FROM THE ELECTRON MASS, m

Mass and Energy

m = 0.510976 Mev = 1/1836.12 m_p = 1/273.26 m_π
Rydberg, $R_\infty = \frac{me^4}{2\hbar^2} = mc^2 \times \frac{\alpha^2}{2}$ = 13.605 ev

Length (1 fermi = 10^{-13} cm; 1 Å = 10^{-8} cm)
$r_e = e^2/mc^2$ = 2.81785 fermi
$ƛ_{Compton} = \frac{\hbar}{mc} = r_e\alpha^{-1}$ = 3.8612 $\times 10^{-11}$ cm
$a_{\infty Bohr} = \frac{\hbar^2}{me^2} = r_e\alpha^{-2}$ = 0.52917 Å

Cross Section
$\sigma_{Thompson} = \frac{8}{3}\pi r_e^2$ = 0.6652$\times 10^{-24}$ cm^2 = 0.6652 barn

(continued below)

Atomic & Nuclear Constants

Table IV (continued)

QUANTITIES DERIVED FROM THE MASS OF THE CHARGED PION, m_π

Rest mass = 139.63 Mev/c^2 = 273.26 m_e = 0.14882 m_p

Length
$\frac{\hbar}{m_\pi c}$ = 1.4132 fermi (~$\sqrt{2}$ fermi)

Natural (≈ "geometrical") Nucleon Cross Section
$\pi\left(\frac{\hbar}{m_\pi c}\right)^2$ = 62.7344 mb (1 mb = 10^{-27} cm^2)

(3/2, 3/2)πp Resonance
Center-of-mass momentum: p_π = 230 Mev/c
Lab-system momentum: P_π = 303 Mev/c (T_π = 194 Mev)

RADIOACTIVITY
1 curie = 3.7 $\times 10^{10}$ disintegrations/sec
1 r = 87.8 ergs/g air = 5.49$\times 10^7$ Mev/g air
Fluxes (per cm^2) to liberate 1 r in carbon:
3 $\times 10^7$ minimum ionizing singly charged particles
0.9$\times 10^9$ photons of 1 Mev energy.
(These fluxes are actually correct to within a factor of two for all materials.)
Natural background: 100 mr/year
"Tolerance" 100 millirem/week [Note, 1 r may produce up to 10 "rem" (r equivalent for man), depending on type of radiation.]

MISCELLANEOUS

Physical Constants
1 year = 3.1536$\times 10^7$ sec (≈ π$\times 10^7$ sec)
Density of air = 1.205 mg/cm^3 at 20°C
Acceleration by gravity = 980.67 cm/sec^2
1 calorie = 4.184 joules
1 atmosphere = 1033.2 g/cm^2

Numerical Constants
1 radian = 57.29578 deg; e = 2.71828
ln 2 = 0.69315; $\log_{10}$ e = 0.43429;
ln 10 = 2.30259; $\log_{10}$ 2 = 0.30103.

Stirling's approximation
$\sqrt{2\pi n}\left(\frac{n}{e}\right)^n < n! < \sqrt{2\pi n}\left(\frac{n}{e}\right)^n\left(1 + \frac{1}{12n-1}\right)$

Gaussianlike Distributions
For n > −1 but not necessarily integral:
$\int_0^\infty x^{2n+1}\exp\left[-\frac{x^2}{2\sigma^2}\right]dx = 2^n\, n!\, \sigma^{2n+2}$; $(\frac{1}{2})! = \sqrt{\pi}/2$

Relation between standard deviation σ and mean deviation α:
$2\sigma^2 = \pi\alpha^2$; σ = 1.4826 probable error.

Odds against exceeding one standard deviation = 2.15:1
two, 21:1; three, 370:1; four, 16,000:1;
five, 1,700,000:1

[a]Based mainly on Cohen, Crowe, and Dumond, The Fundamental Constants of Physics (Interscience, New York, 1957).
[b]C. Sommerfield, Phys. Rev. 107, 328 (1957).

Physical Constants, Num'l Constants, Gaussian Dist's, etc.

Table II

Atomic and nuclear properties (dE/dx, collision mean free path, radiation length, etc.) of materials used as absorbers and detectors

Material	Z	A	Cross section σ [a] (barns)	dE/dx min [b] Mev g/cm²	Collision [a] length, L_{coll} g/cm²	cm	Radiation [c] length, L_{rad} g/cm²	cm	Density ρ (g/cm³)
H_2	1	1.01	0.063	4.14	26.5	374	58	819.0	0.0708
Li	3	6.94	0.23	1.72	50.4	94.3	77.5	145	0.534
C	6	12.00	0.33	1.86	60.4	39.0	42.5	27.4	1.55 (variable)
Al	13	26.97	0.57	1.66	79.2	29.3	23.9	8.86	2.70
Cu	29	63.57	1.00	1.45	105.4	11.8	12.8	1.44	8.9
Sn	50	118.70	1.55	1.27	129.7	17.8	8.54	1.17	7.30
Pb	82	207.21	2.20	1.12	156.2	13.8	5.8	0.51	11.34
U	92	238.07	2.42	1.095	163.6	8.75	5.5	0.29	18.7
Hydrogen (bubble chamber, 27.6°K)				0.243 Mev/cm	26.5	452	58	990	0.0586
Propane (C_3H_8, bubble chamber)				0.935 Mev/cm	48.9	119.3	44.7	109.0	0.41
Polystyrene (CH scintillator)				2.14 Mev/cm	54.9	52.3	43.4	41.3	~1.05
Ilford emulsion				5.49 Mev/cm	103	27.0	11.2	2.91	3.815

dE/dx, Radiation lengths, etc.

Table III

Multiple scattering (Coulomb only) calculated from Molière theory.

θ_{mp} is the mean projected angle in radians between tangents to the particle trajectories:

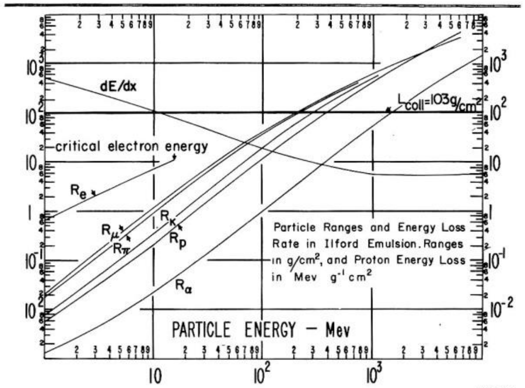
$|\theta|_{average} = \theta_{mp} = \frac{12(Mev)}{p v(Mev)}\sqrt{\frac{L}{L_{rad}}}(1 + \epsilon)$ *

L is the thickness, and L_{rad} the radiation length (from Table II) for the absorber (atomic number Z).
For particles of charge ze and velocity βc, the following table for ε applies:

Z \ L/L_{rad}	10^{-3}	10^{-2}	10^{-1}	1	10	
1	−0.20	−0.14	−0.08	−0.03	+0.02	β/z = 0.1 (4.7-Mev proton)
6	−0.14	−0.07	−0.00	+0.06	+0.12	
29	−0.18	−0.10	−0.01	+0.06	+0.13	
82	−0.27	−0.16	−0.07	+0.02	+0.10	
1	−0.26	−0.20	−0.14	−0.08	−0.03	β/z = 0.3 (45-Mev proton)
6	−0.20	−0.12	−0.05	+0.01	+0.07	
29	−0.20	−0.11	−0.03	+0.05	+0.12	
82	−0.28	−0.17	−0.07	+0.08	+0.09	
1	−0.31	−0.24	−0.18	−0.12	−0.07	β/z = 0.7 (380-Mev proton)
6	−0.26	−0.18	−0.10	+0.03	+0.03	
29	−0.25	−0.15	−0.06	+0.02	+0.09	
82	−0.29	−0.17	−0.08	−0.01	+0.09	
1	−0.34	−0.26	−0.20	−0.14	−0.08	β/z = 1.0
6	−0.29	−0.20	−0.12	−0.05	−0.01	
29	−0.34	−0.23	−0.13	−0.05	−0.03	
82	−0.31	−0.19	−0.09	−0.00	−0.08	

*Note that in the Gaussian approximation the root-mean-square projected angle is obtained from the formula above by substituting 15 for the coefficient 12.

Multiple Scattering



Particle Ranges, Energy Loss Rates

PDG Database 1980

Art Rosenfeld
1975 review article

THE PARTICLE DATA GROUP: GROWTH AND OPERATIONS

Excerpts:

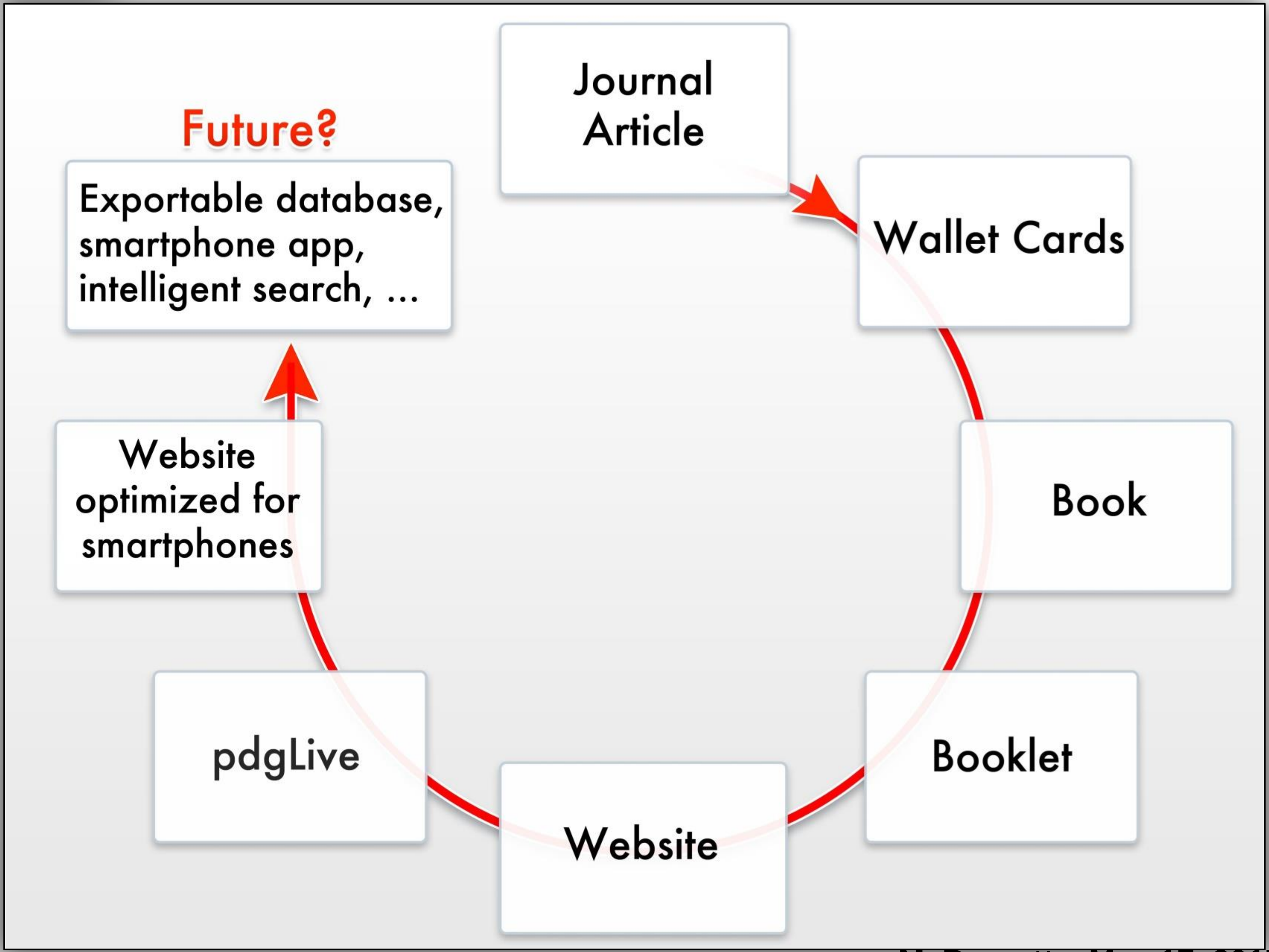
A single international group, the Particle Data Group (PDG), compiles all the data on particle properties.

We briefly discuss how the data rate grew from a trickle to a fairly steady flood.... We outline how PDG has learned to collect, evaluate, correct, verify, analyze, and distribute the data,… PDG has taken on the responsibility of critically reviewing the results of experiments.

Of over 154 pages of "Listings," 50 pages are actually not listings, but figures, or …reviews.

In our experience, transatlantic collaboration works surprisingly well, but only after people have worked together and grown to know one another well.

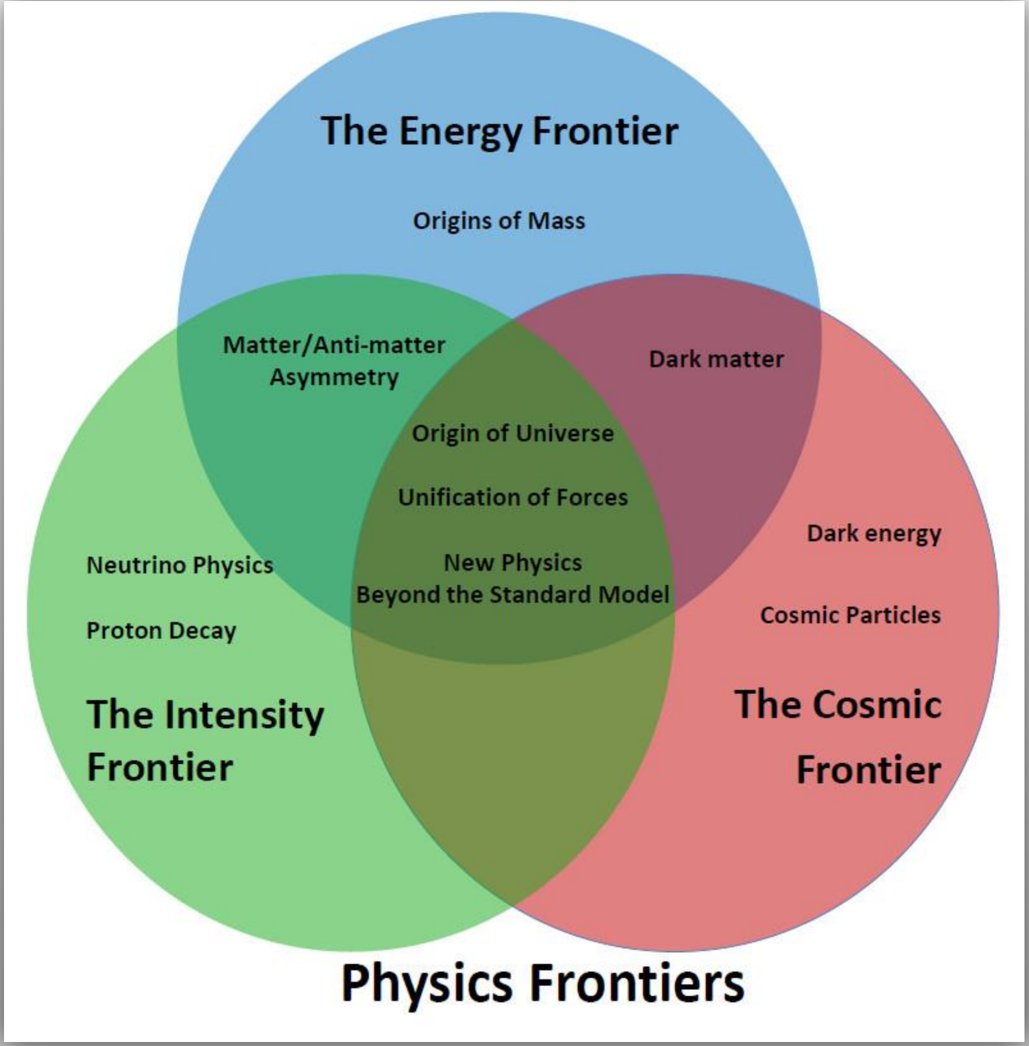
PDG Innovations



When we talk to DOE…

PDG leverages all frontier areas:

- **Energy,**
- **Intensity,**
- **Cosmic.**



The Essence of PDG

- **Listings of Data**
  (with Summary Tables)

- **Reviews of Essential Topics**

- **pdgLive**
  (an interactive combination of Listings and Reviews)

Listings and Reviews

The Web allows us to see what most interest our readers.

The hits (page views) on

Data Listings = Reviews

almost exactly equal.

Clearly people care about both.

What PDG Produces

Printed – updated in even years

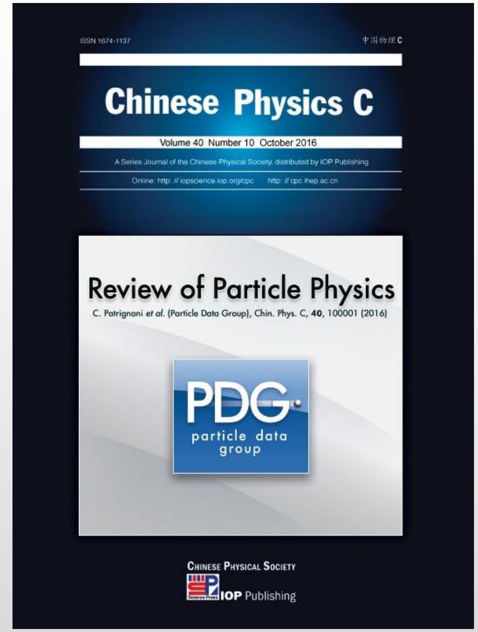
- **Book – 14,000 copies**
- **Booklet – 32,000 copies**

Online – updated once a year.

More than 100 million hits total.

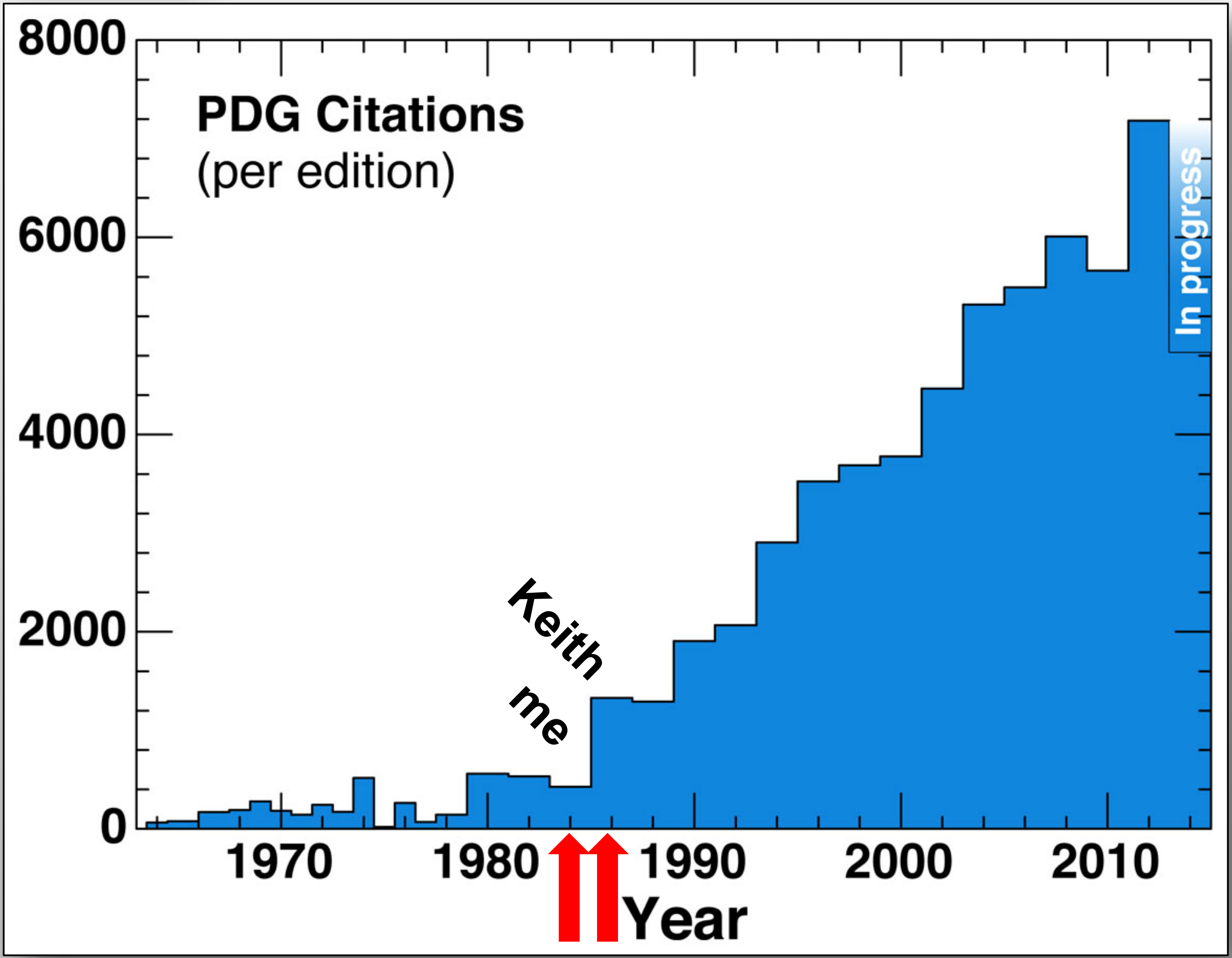
- **Full content of the book (PDF)**
- **pdgLive – Interactive web app**

All the content as the PDF files. Cross-linked with INSPIRE, which is cross-linked with others.



8 Mirror sites

PDG Citations



What Keith Does for PDG

Everything

What Keith Does for PDG

1) Write Reviews (since 1986)

2) Data Listings (since 1988)
For Astrophysical data on:
SUSY, Axions, Neutrinos, Technicolor, Compositeness, Extra Dimensions.

3) Manage Reviews (since 1996; now 8 reviews)

PDG particle data group

We have a special page for astrophysics & cosmology

PDG particle data group

Astrophysics & Cosmology

HOME: | pdgLive | Summary Tables | Reviews, Tables, Plots | Particle Listings

All astrophysical and cosmology coverage in the Review of Particle Physics.

Astrophysical Constants and Parameters

Astrophysical Constants and Parameters ← **1986**

Reviews **Reviews**

- Experimental tests of gravitational theory
- Big-Bang cosmology ← **1986**
- Inflation
- Big-Bang nucleosynthesis
- Cosmological parameters
- Dark matter
- Dark energy
- Cosmic microwave background
- Cosmic rays
- Neutrino mass, mixing, and oscillations

Data Listings **Data Listings**

- Axions
- Supersymmetry
- Neutrinos
- Neutrino Properties
- Number of Neutrino Types
- Neutrino Mixing
- Heavy Neutral Leptons, Searches for

The beginning: Big Bang Cosmology

1986

BIG BANG COSMOLOGY*

All observational evidence to date indicates that our universe is very nearly homogeneous and isotropic. The most general space-time interval with these properties is the Friedmann-Robertson-Walker metric (with $c = 1$)

$$ds^2 = dt^2 - R^2(t)\left[\frac{dr^2}{1 - \kappa r^2} + r^2(d\theta^2 + \sin^2\theta\, d\phi^2)\right],$$

where $\kappa = +1$, -1 or 0 corresponds to closed, open, or spatially flat geometries. $R(t)$ is a scale factor for distances in comoving coordinates. Einstein's equations lead to the Friedmann equation

$$H^2 \equiv \left(\frac{\dot R}{R}\right)^2 = \frac{8\pi G_N \rho}{3} - \frac{\kappa}{R^2} + \frac{\Lambda}{3}$$

as well as to

$$\frac{\ddot R}{R} = \frac{\Lambda}{3} - \frac{4\pi G_N}{3}(\rho + 3p)$$

where $H(t)$ is the Hubble parameter, ρ is the total mass-energy density, p is the isotropic pressure, and Λ is the cosmological constant. (For limits on Λ, see the Table of Astrophysical Constants; we will assume here $\Lambda = 0$.) The Friedmann equation serves to define the density parameter Ω_0 (subscript 0 indicates present-day values)

$$\kappa/R_0^2 = H_0^2(\Omega_0 - 1) \qquad \Omega_0 = \rho_0/\rho_c$$

and the critical density is defined as

$$\rho_c \equiv \frac{3H_0^2}{8\pi G_N} = 1.88\times 10^{-26}\, h_0^2 \text{ kg m}^{-3},$$

with

$$H_0 = 100 h_0 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

Observational bounds give $0.4 < h_0 < 1$. The three possible values of κ, $+1$, -1, and 0, correspond to $\Omega_0 > 1$, < 1 and $= 1$, i.e. to closed, open, and flat (critical) universes. The value of Ω_0 is inferred from velocity measurements on scales greater than 100 kpc, which are all consistent with $0.1 \lesssim \Omega_0 \lesssim 0.4$. Conservative bounds are $0.05 \lesssim \Omega_0 \lesssim 4$. The portion of Ω in luminous matter is much smaller, $0.005 \lesssim \Omega_{lum} \lesssim 0.02$. The excess of Ω_0 over Ω_{lum} leads to the inference that most of the matter in the universe is nonluminous "dark" matter.

Energy conservation implies that $\dot\rho = -3(\dot R/R)(\rho + p)$, so that for a matter-dominated ($p = 0$) universe $\rho \propto R^{-3}$, while for a radiation-dominated ($p = 1/3\rho$) universe $\rho \propto R^{-4}$. Thus the less singular curvature term κ/R^2 in the Friedmann equation can be neglected at early times when R is small. Energy conservation also implies that the universe expands adiabatically, $R^3 s$ = constant, where the entropy density $s = (\rho + p)/T$ and T is temperature.

The energy density of radiation can be expressed as

$$\rho_r = \frac{\pi^2 k^4}{30} N(T)T^4$$

with $\hbar = 1$, where $N(T)$ counts the effectively massless degrees of freedom of bosons and fermions

$$N(T) = \sum_B g_B + \frac{7}{8}\sum_F g_F$$

For example, for $m_\mu > kT > m_e$, $N(T) = g_\gamma + 7/8(g_e + 3g_\nu) = 2 + 7/8[4 + 3(2)] = 43/4$. For $m_\pi > kT > m_\mu$, $N(T) = 57/4$.

In the early universe when $\rho \sim \rho_r$, then $\dot R \sim 1/R$ so that $R \propto t^{1/2}$ and $Ht \to 1/2$; the time-temperature relation then follows

$$t = 2.4[N(T)]^{-1/2}\left(\frac{1\text{MeV}}{kT}\right)^2 \text{s}$$

Today, the energy density in photons is $\rho_\gamma = (\pi^2k^4/15)T_0^4$, where the present temperature of the microwave background is $T_0 = 2.73 \pm 0.05$K, and the number density of photons n_γ is $400(T_0/2.7\text{K})^3 \text{ cm}^{-3}$. For nonrelativistic matter (such as baryons) today, the energy density is $\rho_B = m_B n_B$ with $n_B \propto R^{-3}$, so that for most of the history of the universe n_B/s is constant. Today, the entropy density is related to the photon density by $s \sim 7n_\gamma$. Big Bang nucleosynthesis calculations limit $\eta = n_B/n_\gamma$ to $3\times 10^{-10} < \eta < 10^{-9}$. The parameter η is also related to the portion of Ω in baryons

$$\Omega_B = 3.6\times 10^7 \eta h_0^{-2}(T_0/2.7\text{K})^3,$$

so that $0.01 < \Omega_B h_0^2 < 0.04$ and hence the universe cannot be closed by baryons.

* Written December 1985 by K. A. Olive and S. Rudaz.

Sum of Neutrino Masses

1988

<132 eV

NEUTRINO BOUNDS FROM ASTROPHYSICS & COSMOLOGY

LIMIT ON TOTAL ν MASS, m(tot)

(Defined in the above note) of effectively stable neutrinos (i.e., those with mean lives greater than or equal to the age of the universe). These papers assumed Dirac neutrinos. When necessary we have generalized the results reported so they apply to m(tot). For other limits see SZALAY 76, VYSOTSKY 77, BERNSTEIN 81, FREESE 84, SCHRAMM 84 and COWSIK 85

VALUE (eV)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<180	SZALAY	74	COSM
<132	COWSIK	72	COSM
<280	MARX	72	COSM
<400	GERSHTEIN	66	COSM

LIMITS ON NEUTRINO MASS FOR $m(\nu)$ > 1 MeV

For other limits, see SATO 77, DICUS 78, HUT 79, and BERNSTEIN 85

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 20–1000	95	[1] GELMINI	87	COSM	Dirac ν
>15		[1,2] GAISSER	86	COSM	Dirac ν
>27		[1,2] GAISSER	86	COSM	Majorana ν
> 3		KOLB	86	COSM	Dirac ν
> 7		KOLB	86	COSM	Majorana ν
> 3		HUT	77	COSM	
> 2		LEE	77	COSM	Dirac ν
> 2.5		VYSOTSKY	77	COSM	

[1] These results assume that neutrinos make up dark matter in the galactic halo.

[2] Limits based on annihilations in the sun and are due to an absence of high energy neutrinos detected in underground experiments.

ASTROPHYSICAL AND COSMOLOGICAL LIMITS ON ν MASSES

If neutrinos are present as dark matter in galactic halos, limits on neutrino masses have been computed based on neutrino degeneracy and Fermi statistics. The results depend strongly on assumptio[ns] ... references

GOLDMAN	79	COSM
LINDLEY	79	COSM
DICUS	78	COSM
DICUS	78B	COSM
FALK	78	COSM
GUNN	78	COSM
MIYAMA	78	COSM
COWSIK	77	COSM
DICUS	77	COSM
GOLDMAN	77	COSM

NUMBER OF LIGHT TWO-COMPONENT ν TYPES
("light" means < about 1 MeV)

NUMBER COUPLING WITH FULL WEAK STRENGTH

See also STECKER 80B, OLIVE 81B, STECKER 81, and RANA 82

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<5.2	ELLIS	86	COSM	
<4	STEIGMAN	86	COSM	
<4	YANG	84	COSM	
10 to 1000	ELLIS	83	COSM	Astrophys model dep
maybe no firm bound	OLIVE	81	COSM	
<4	YANG	79	COSM	
<7	STEIGMAN	77	COSM	
	SHVARTSMAN	69	COSM	

NUMBER COUPLING WITH LESS THAN FULL WEAK STRENGTH

VALUE	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<20	[5] OLIVE	81C	COSM
<20	[5] STEIGMAN	79	COSM

[5] Limit varies with strength of coupling

2016

<0.15 eV

SUM OF THE NEUTRINO MASSES, m_{tot}

(Defined in the above note), of effectively stable neutrinos (i.e., those with mean lives greater than or equal to the age of the universe). These papers assumed Dirac neutrinos. When necessary, we have generalized the results reported so they apply to m_{tot}. For other limits, see SZALAY 76, VYSOTSKY 77, BERNSTEIN 81, FREESE 84, SCHRAMM 84, and COWSIK 85.

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 0.15	95	[1] PALANQUE-...	15	COSM	SDSS/BOSS
< 0.12	95	[2] PALANQUE-...	15A	COSM	SDSS/BOSS
< 0.23	95	[3] ADE	14	COSM	Planck
0.320 $\pm$ 0.081		[4] BATTYE	14	COSM	
0.35 $\pm$ 0.10		[5] BEUTLER	14	COSM	BOSS
0.22 $^{+0.09}_{-0.10}$		[6] COSTANZI	14	COSM	
< 0.22	95	[7] GIUSARMA	14	COSM	

ASTROPHYSICAL CONSTANTS AND PARAMETERS

Quantity	Symbol, equation	Value	Reference, footnote
speed of light	c	$299\,792\,458$ m s^{-1}	exact[4]
Newtonian constant of gravitation	G_N	$6.674\,08(31) \times 10^{-11}$ m^3 kg^{-1} s^{-2}	[1]
Planck mass	$\sqrt{\hbar c/G_N}$	$1.220\,910(29) \times 10^{19}$ GeV$/c^2 = 2.176\,47(5) \times 10^{-8}$ kg	[1]
Planck length	$\sqrt{\hbar G_N/c^3}$	$1.616\,229(38) \times 10^{-35}$ m	[1]
standard acceleration of gravity	g_N	$9.806\,65$ m s^{-2}	exact[1]
jansky (flux density)	Jy	10^{-26} W m^{-2} Hz^{-1}	definition
tropical year (equinox to equinox) (2011)	yr	$31\,556\,925.2$ s $\approx \pi \times 10^7$ s	[5]
sidereal year (fixed star to fixed star) (2011)		$31\,558\,149.8$ s $\approx \pi \times 10^7$ s	[5]
mean sidereal day (2011) (time between vernal equinox transits)		$23^{\rm h}\,56^{\rm m}\,04.^{\rm s}090\,53$	[5]
astronomical unit	au	$149\,597\,870\,700$ m	exact[6]
parsec (1 au/1 arc sec)	pc	$3.085\,677\,581\,49 \times 10^{16}$ m $= 3.262\ldots$ ly	exact[7]
light year (deprecated unit)	ly	$0.306\,6\ldots$ pc $= 0.946\,053\ldots \times 10^{16}$ m	
Schwarzschild radius of the Sun	$2G_N M_\odot/c^2$	$2.953\,250\,24$ km	[8]
Solar mass	$M_\odot$	$1.988\,48(9) \times 10^{30}$ kg	[9]
nominal Solar equatorial radius	$\mathcal{R}_\odot$	6.957×10^8 m	exact[10]
nominal Solar constant	$\mathcal{S}_\odot$	1361 W m^{-2}	exact[10,11]
nominal Solar photosphere temperature	$\mathcal{T}_\odot$	5772 K	exact[10]
nominal Solar luminosity	$\mathcal{L}_\odot$	3.828×10^{26} W	exact[10,12]
Schwarzschild radius of the Earth	$2G_N M_\oplus/c^2$	$8.870\,056\,580(18)$ mm	[13]
Earth mass	$M_\oplus$	$5.972\,4(3) \times 10^{24}$ kg	[14]
nominal Earth equatorial radius	$\mathcal{R}_\oplus$	6.3781×10^6 m	exact[10]
luminosity conversion	L	$3.0128 \times 10^{28} \times 10^{-0.4\,M_{\rm bol}}$ W	[15]
		($M_{\rm bol}$ = absolute bolometric magnitude = bolometric magnitude at 10 pc)	
flux conversion	$\mathscr{F}$	$2.5180 \times 10^{-8} \times 10^{-0.4\,m_{\rm bol}}$ W m^{-2}	[15]
		($m_{\rm bol}$ = apparent bolometric magnitude)	
ABsolute monochromatic magnitude	AB	$-2.5\log_{10} f_\nu - 56.10$ (for f_ν in W m^{-2} Hz^{-1})	[16]
		$= -2.5\log_{10} f_\nu + 8.90$ (for f_ν in Jy)	
Solar angular velocity around the Galactic center	Θ_0/R_0	30.3 ± 0.9 km s^{-1} kpc^{-1}	[17]
Solar distance from Galactic center	R_0	8.00 ± 0.25 kpc	[17,18]
circular velocity at R_0	v_0 or Θ_0	$254(16)$ km s^{-1}	[17]
escape velocity from Galaxy	$v_{\rm esc}$	498 km/s $< v_{\rm esc} < 608$ km/s	[19]
local disk density	$\rho_{\rm disk}$	3–12 $\times 10^{-24}$ g cm$^{-3} \approx$ 2–7 GeV$/c^2$ cm^{-3}	[20]
local dark matter density	ρ_χ	canonical value 0.3 GeV$/c^2$ cm^{-3} within factor 2–3	[21]
present day CMB temperature	T_0	$2.7255(6)$ K	[22,24]
present day CMB dipole amplitude		$3.3645(20)$ mK	[22,23]
Solar velocity with respect to CMB		$369(1)$ km s^{-1} towards $(\ell, b) = (263.99(14)^\circ, 48.26(3)^\circ)$	[22,25]
Local Group velocity with respect to CMB	$v_{\rm LG}$	$627(22)$ km s^{-1} towards $(\ell, b) = (276(3)^\circ, 30(3)^\circ)$	[22,25]
number density of CMB photons	n_γ	$410.7(T/2.7255)^3$ cm^{-3}	[26]
density of CMB photons	ρ_γ	$4.645(4)\,(T/2.7255)^4 \times 10^{-34}$ g cm$^{-3} \approx 0.260$ eV cm^{-3}	[26]
entropy density/Boltzmann constant	s/k	$2\,891.2\,(T/2.7255)^3$ cm^{-3}	[26]
present day Hubble expansion rate	H_0	$100\,h$ km s^{-1} Mpc$^{-1} = h \times (9.777\,752$ Gyr$)^{-1}$	[27]
scale factor for Hubble expansion rate	h	$0.678(9)$	[2,3]
Hubble length	c/H_0	$0.925\,0629 \times 10^{26}\,h^{-1}$ m $= 1.374(18) \times 10^{26}$ m	
scale factor for cosmological constant	$c^2/3H_0^2$	$2.85247 \times 10^{51}\,h^{-2}$ m$^2 = 6.20(17) \times 10^{51}$ m^2	
critical density of the Universe	$\rho_{\rm crit} = 3H_0^2/8\pi G_N$	$1.878\,40(9) \times 10^{-29}\,h^2$ g cm^{-3}	
		$= 1.053\,71(5) \times 10^{-5}\,h^2$ (GeV$/c^2$) cm^{-3}	
		$= 2.775\,37(13) \times 10^{11}\,h^2\,M_\odot$ Mpc^{-3}	
baryon-to-photon ratio (from BBN)	$\eta = n_{\rm b}/n_\gamma$	$5.8 \times 10^{-10} \le \eta \le 6.6 \times 10^{-10}$ (95% CL)	[28]
number density of baryons	$n_{\rm b}$	$2.503(26) \times 10^{-7}$ cm^{-3}	[2,3,29,30]
		$(2.4 \times 10^{-7} < n_{\rm b} < 2.7 \times 10^{-7})$ cm^{-3} (95% CL)	$\eta \times n_\gamma$
CMB radiation density of the Universe	$\Omega_\gamma = \rho_\gamma/\rho_{\rm crit}$	$2.473 \times 10^{-5}(T/2.7255)^4\,h^{-2} = 5.38(15) \times 10^{-5}$	[26]
- - - *Planck* 2015 6-parameter fit to flat ΛCDM cosmology - - -			
baryon density of the Universe	$\Omega_{\rm b} = \rho_{\rm b}/\rho_{\rm crit}$	$^\ddagger 0.02226(23)\,h^{-2} = {}^\dagger 0.0484(10)$	[2,3,23]
cold dark matter density of the universe	$\Omega_{\rm CDM} = \rho_{\rm CDM}/\rho_{\rm crit}$	$^\ddagger 0.1186(20)\,h^{-2} = {}^\dagger 0.258(11)$	[2,3,23]
100 × approx to $r_*/D_{\rm A}$	$100 \times \theta_{\rm MC}$	$^\ddagger 1.0410(5)$	[2,3]
reionization optical depth	τ	$^\ddagger 0.066(16)$	[2,3]
scalar spectral index	$n_{\rm s}$	$^\ddagger 0.968(6)$	[2,3]
ln pwr primordial curvature pert. (k_0=0.05 Mpc^{-1})	$\ln(10^{10}\Delta^2_{\mathcal{R}})$	$^\ddagger 3.062(29)$	[2,3]

2016

dark energy density of the ΛCDM Universe	Ω_Λ	$^\dagger 0.692 \pm 0.012$	[2,3]
pressureless matter density of the Universe	$\Omega_{\rm m} = \Omega_{\rm CDM} + \Omega_{\rm b}$	$^\dagger 0.308 \pm 0.012$	[2,3]
fluctuation amplitude at $8\,h^{-1}$ Mpc scale	σ_8	$^\dagger 0.815 \pm 0.009$	[2,3]
redshift of matter-radiation equality	$z_{\rm eq}$	$^\dagger 3365 \pm 44$	[2]
redshift at which optical depth equals unity	z_*	$^\dagger 1089.9 \pm 0.4$	[2]
comoving size of sound horizon at z_*	r_*	$^\dagger 144.9 \pm 0.4$ Mpc (*Planck* CMB)	[31]
age when optical depth equals unity	t_*	373 kyr	[32]
redshift at half reionization	$z_{\rm reion}$	$^\dagger 8.8^{+1.7}_{-1.4}$	[2]
redshift when acceleration was zero	z_q	~ 0.65	[32]
age of the Universe	t_0	$^\dagger 13.80 \pm 0.04$ Gyr	[2]
effective number of neutrinos	$N_{\rm eff}$	$^\sharp 3.1 \pm 0.6$	[2,33]
sum of neutrino masses	$\sum m_\nu$	$^\sharp < 0.68$ eV (Planck CMB); ≥ 0.05 eV (mixing)	[2,34,35]
neutrino density of the Universe	$\Omega_\nu = h^{-2}\sum m_{\nu_j}/93.04\,{\rm eV}$	$^\sharp < 0.016$ (Planck CMB; ≥ 0.0012 (mixing)	[2,34,35]
curvature	Ω_K	$^\sharp -0.005^{+0.016}_{-0.017}$ (95%CL)	[2]
running spectral index slope, $k_0 = 0.002$ Mpc^{-1}	$dn_{\rm s}/d\ln k$	$^\sharp -0.003(15)$	[2]
tensor-to-scalar field perturbations ratio, k_0=0.002 Mpc^{-1}	$r_{0.002} = T/S$	$^\sharp < 0.114$ at 95% CL; no running	[2,3]
dark energy equation of state parameter	w	-0.97 ± 0.05	[31,36]
primordial helium fraction	$Y_{\rm p}$	0.245 ± 0.004	[22,37]

Within the review of "Cosmological Parameters"

Parameter Constraints

2016

Table 25.1: Parameter constraints reproduced from Ref. 2 (Table 4), with some additional rounding. Both columns assume the ΛCDM cosmology with a power-law initial spectrum, no tensors, spatial flatness, a cosmological constant as dark energy and the sum of neutrino masses fixed to 0.06eV. Above the line are the six parameter combinations actually fit to the data (θ_{MC} is a measure of the sound horizon at last scattering); those below the line are derived from these. The first column uses *Planck* primary CMB data, restricting polarization data to low multipoles as currently recommended by the Planck collaboration, plus the *Planck* measurement of CMB lensing. This column gives our present recommended values. The second column adds additional data and is included to show that the effect of its inclusion is modest; the extra data are the Hubble parameter, BAO measurements from the SDSS, BOSS, and 6dF surveys, and supernova constraints from the JLA analysis. The perturbation amplitude $\Delta^2_{\mathcal{R}}$ (denoted A_{s} in the original paper) is specified at the scale $0.05\,\mathrm{Mpc}^{-1}$. Uncertainties are shown at 68% confidence.

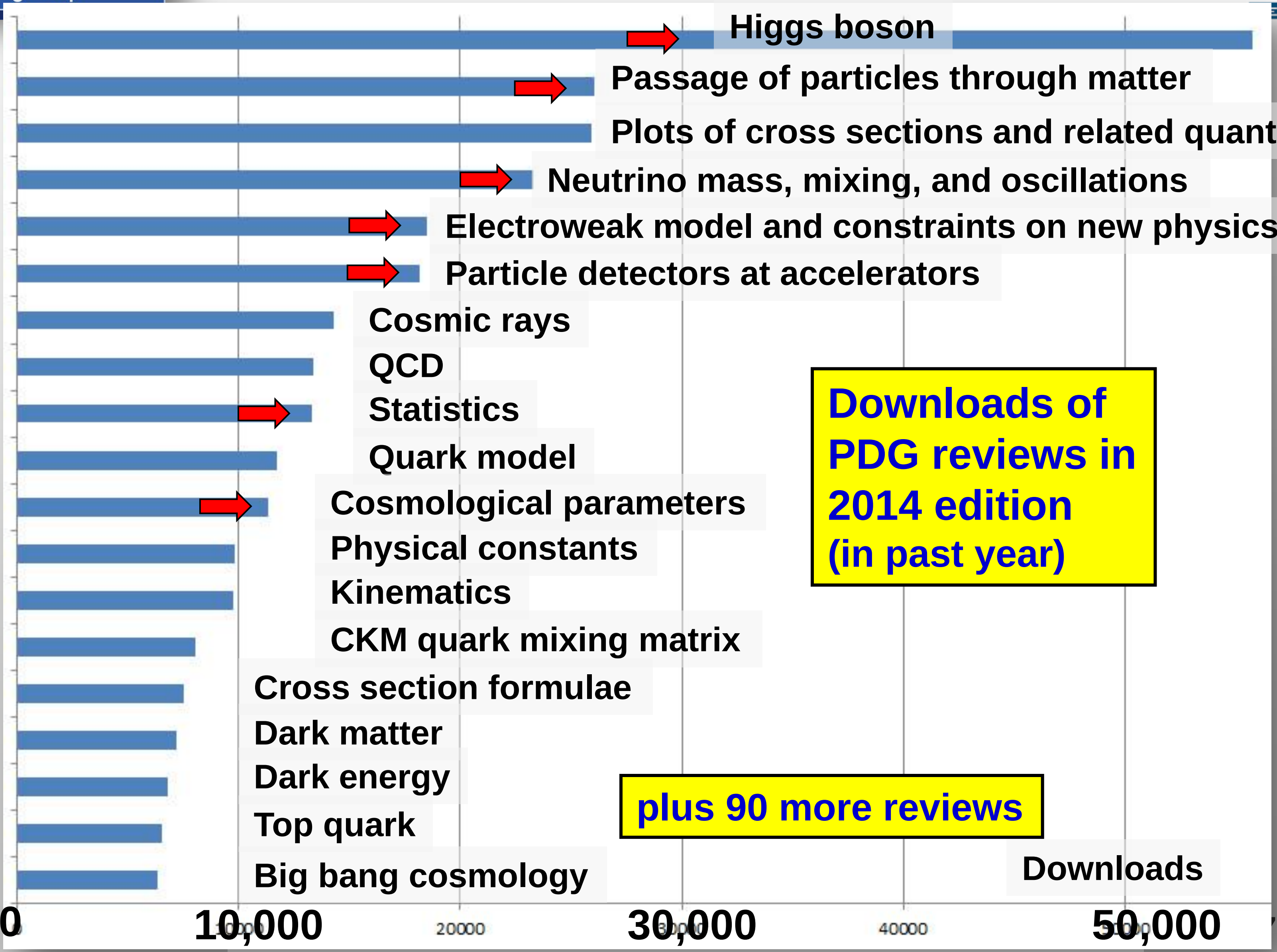
	Planck TT+lowP+lensing	*Planck* TT+lowP+lensing+ext
$\Omega_{\mathrm{b}}h^2$	0.02226 ± 0.00023	0.02227 ± 0.00020
$\Omega_{\mathrm{c}}h^2$	0.1186 ± 0.0020	0.1184 ± 0.0012
$100\,\theta_{\mathrm{MC}}$	1.0410 ± 0.0005	1.0411 ± 0.0004
n_{s}	0.968 ± 0.006	0.968 ± 0.004
τ	0.066 ± 0.016	0.067 ± 0.013
$\ln(10^{10}\Delta^2_{\mathcal{R}})$	3.062 ± 0.029	3.064 ± 0.024
h	0.678 ± 0.009	0.679 ± 0.006
σ_8	0.815 ± 0.009	0.815 ± 0.009
Ω_{m}	0.308 ± 0.012	0.306 ± 0.007
Ω_{Λ}	0.692 ± 0.012	0.694 ± 0.007

Downloads:
2014 edition until 2016 edition released

31,506	The cosmological parameters
21,598	Dark matter
19,873	Astrophysical constants
18,822	Big-Bang cosmology
14,641	Dark energy
11,546	Cosmic microwave background
10,632	Big-Bang nucleosynthesis
8,964	Experimental tests of gravitational theory

Total Cosmology Downloads 137,582 (9.2%)

Amazing Diversity of Topics Interest Our Community



Downloads of PDG reviews in 2014 edition (in past year)

plus 90 more reviews

Year of First Appearance

1986 Big-Bang cosmology

1986 Astrophysical constants

1992 Dark matter

1996 The Hubble Constant

1996 Cosmic microwave background

1996 Big-Bang nucleosynthesis

1998 Experimental tests of gravitational theory

2000 Pocket Cosmology (replaced B.B.C.)

2000 Global cosmological parameters: H^0, Ω_M, Λ (repl. Hubble)

2002 Big-bang cosmology (repl. Pocket)

2004 Cosmological parameters (repl. G.C.P.)

2014 Dark energy

2016 Inflation

9 Reviews:
All coordinated by Keith for consistency, overlap, lack of bias, use of same numbers, etc.

2018 Cosmological neutrino constraints

16 Cosmology Authors 2016

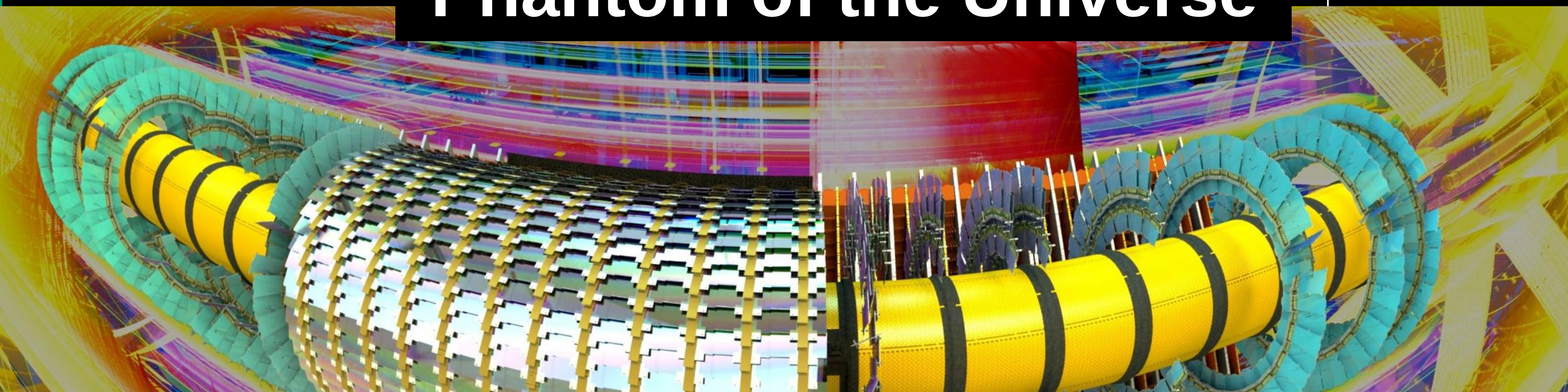
Keith coordinates authors, manages discussions, handles disputes, etc.

- Thibault Damour
- Manuel Drees
- John Ellis
- Brian Fields
- Gilles Gerbier
- Ofer Lahav
- Andrew Liddle
- Paulo Molaro
- Keith Olive
- John Peacock
- Subir Sarkar
- Douglas Scott
- George Smoot
- David Wands
- David Weinberg
- Martin White

And a few more things about PDG and about Outreach

Planetarium Show

Phantom of the Universe



Available now for FREE
to planetariums worldwide.

110 million people a year watch planetarium shows.

http://PhantomOfTheUniverse.org

DARK MATTER

- Galaxies, Clusters, Underground searches & LHC
- Narrator is **Tilda Swinton**, Academy Award-winning actress.
- Sound effects by **Skywalker Sound**
- **Worldwide collab.:** LBNL, UTA, MSU, CERN, Valencia, etc.

Phantom of the Universe

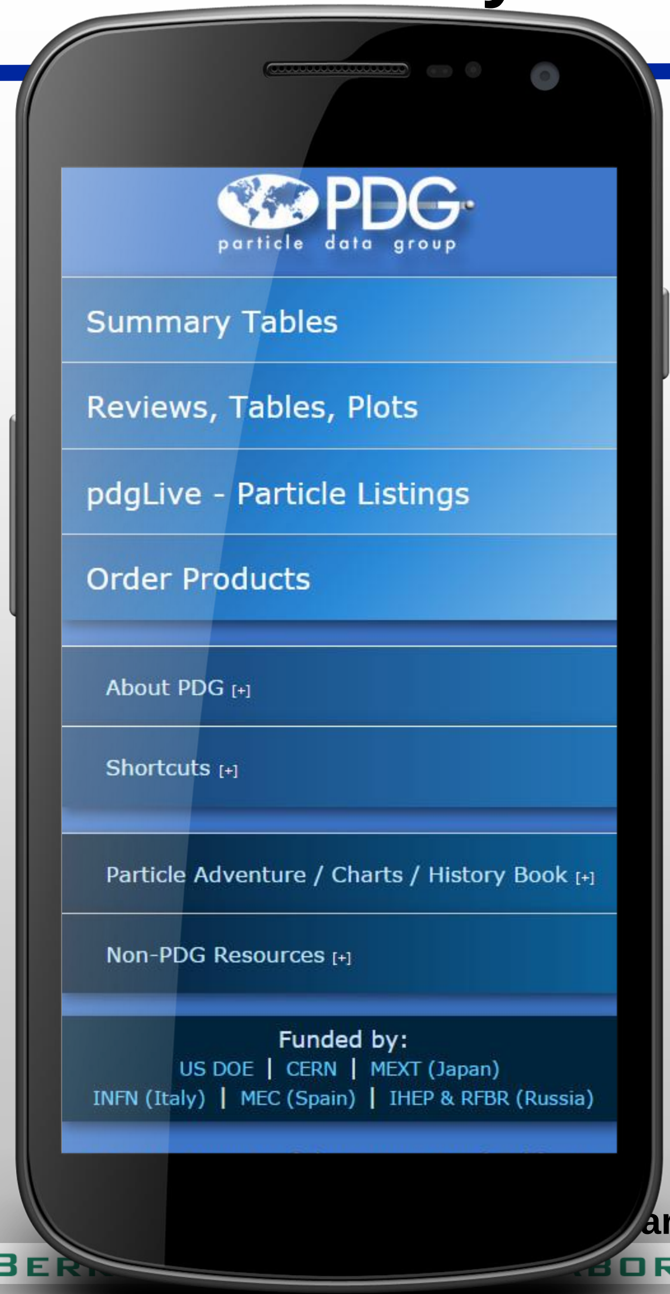
A Planetarium Show

- German version showing in Austria and Germany
- French translation completed; narration soon.
- Nominated for International Full Dome Festival in Germany later this month.

- Showing or scheduled in: 112 Planetariums
- 24 U.S. States.
- All 5 continents. 34 countries. 16 Languages.

Available now for FREE
to planetariums worldwide.
barnett@lbl.gov

New: Mobile-Friendly Version



All the content of the regular site including pdgLive:
The entire book in your pocket.

pdg.lbl.gov

Google now gives priority to mobile-friendly websites for searches from smartphones.

PDG Survey in 2014

Is having a copy of the full-sized book essential to your work or study?

Is a Book without Data Listings OK? (45% as big)
(keeping online Data Listings)

How important is an app?

Similar questions were asked about the Booklet.

PDG Survey in 2014

An amazing 6172 readers responded, demonstrating the very high value our community places on PDG products (and 1495 comments).

The comments occupy 110 pages.

PDG Survey on Book

68% **want the book,
with or without the Data Listings**

2/3 **said app was important or very important.**

82% **want the booklet**

Future Possibilities

– Downloadable PDG data

– pdgLive version for offline use (as an app)

– Emphasis on searching and indexing, rather than navigation

– Interactive plotting, data selection and evaluation

– User tagging or display of contributed content

– Cross-linking with other services (pdgLive ↔ INSPIRE available)

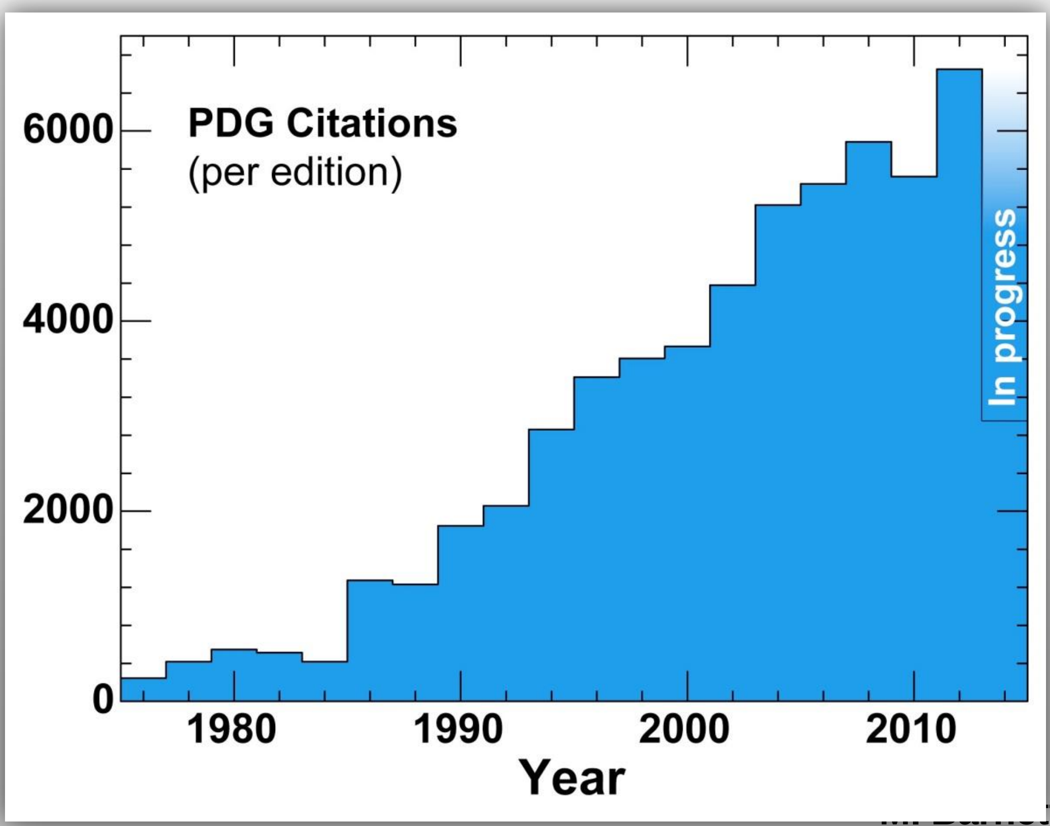
Implementing these new features is a long-term effort given our declining resources

PDG Impact

- 32,000 Booklets requested
- 14,000 RPP books requested
- 9 million hits/year on website (>180 countries)
- 108 million hits on website in total
- 61,000 combined citations of RPP
- Most cited publication in HEP

Top Cited

The Review is the all-time top cited article in High Energy Physics with more than 61,000 citations (INSPIRE) since Keith joined.



Citations increase for years after an edition is published

PDG Summary

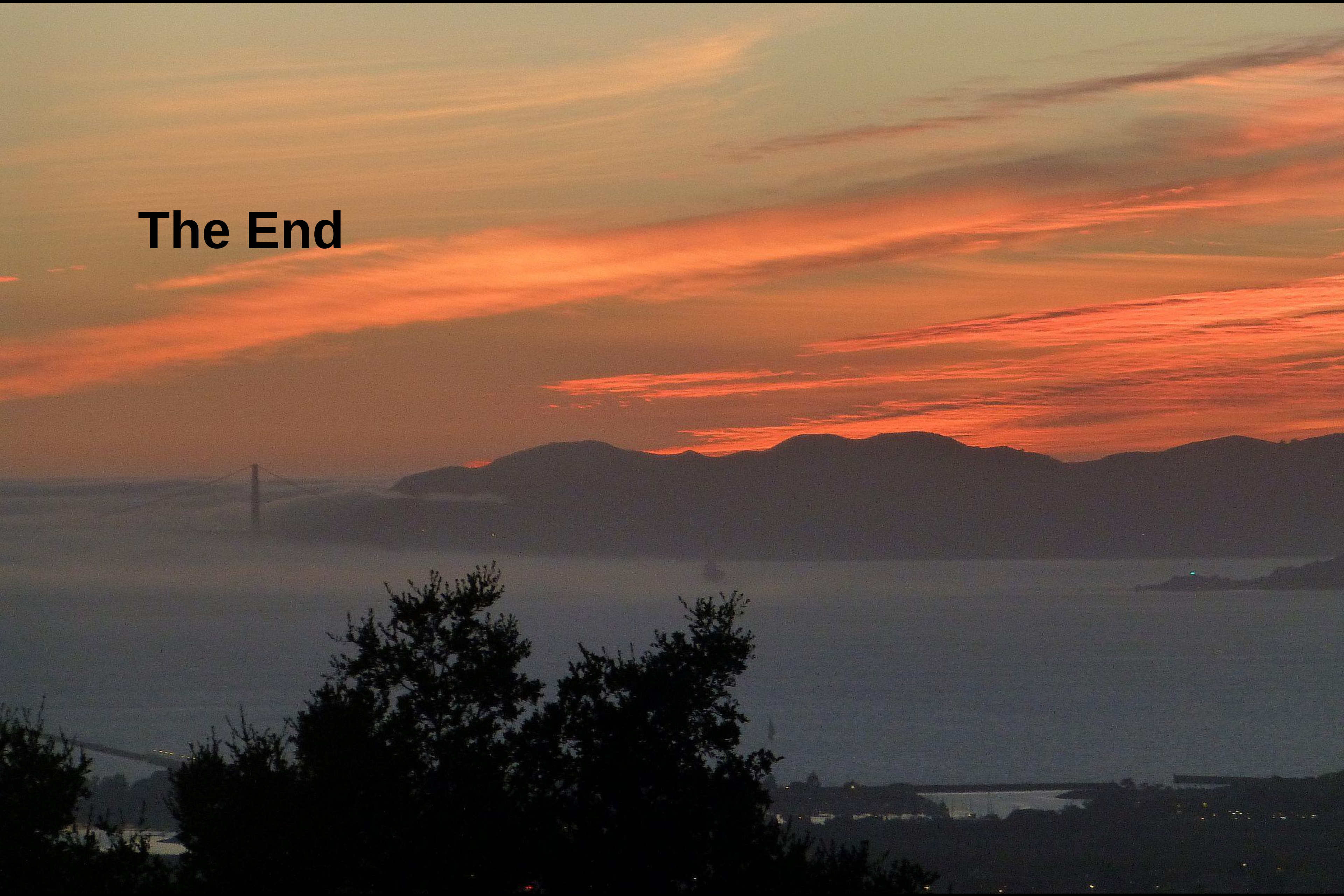
PDG provides a vital, dynamic, innovative service.
It leverages the work of all the HEP community, and
Keith connects us with the astro-cosmology community.

The HEP community depends on PDG to provide standards and to assure integrity and quality in summarizing particle physics. Keith works with 16 authors to assure a coherent whole to his set.

Thank you Keith!

and

Happy Birthday!


The End

Community Connections

PDG Advisory Committee

Collaboration with Working Groups

PDG Workshops

Periodic Surveys

Input from users

Via membership in research collaborations

Collaboration with Working Groups

Working groups:

LHC, Tevatron, B-factories,…

- **Higgs**
- **Electroweak fits,**
- **B lifetimes, B mixing,**
- **V_{cb} and V_{ub}**
- **top quark mass, etc.**

Provide fits to our data using PDG guidelines.

Vital PDG Workshops

With experts lead to improved coverage:

Searches

Higgs

Neutrino

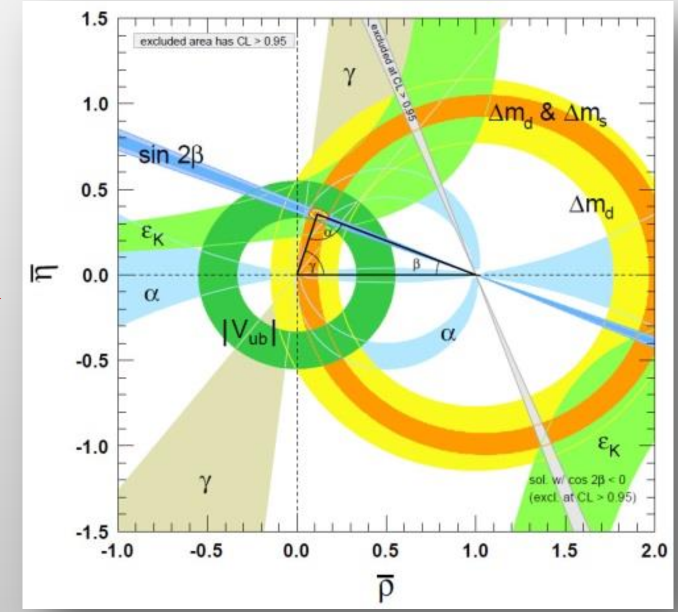
D meson

CKM

τ lepton

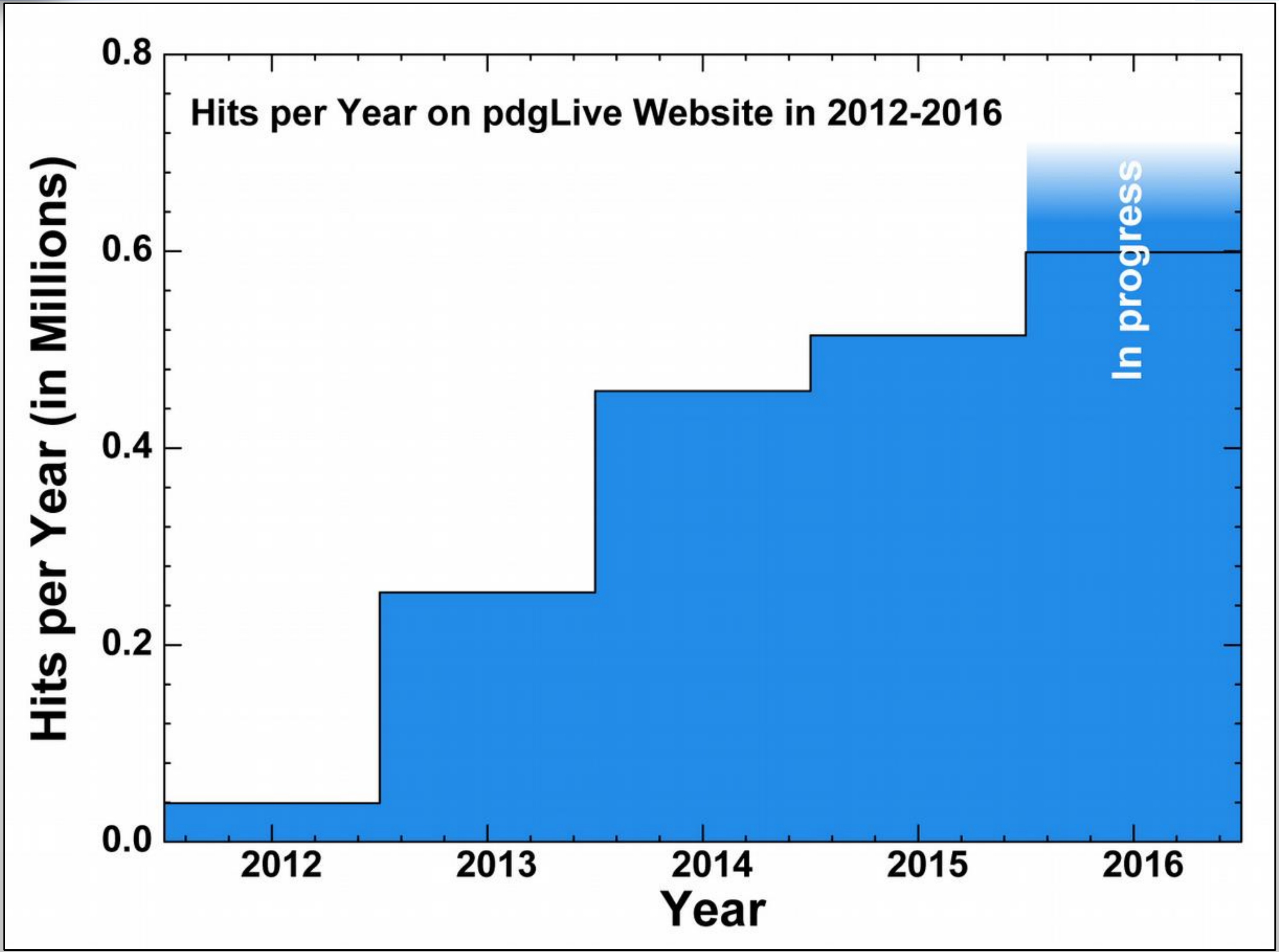
Extra-dimensions

Statistics



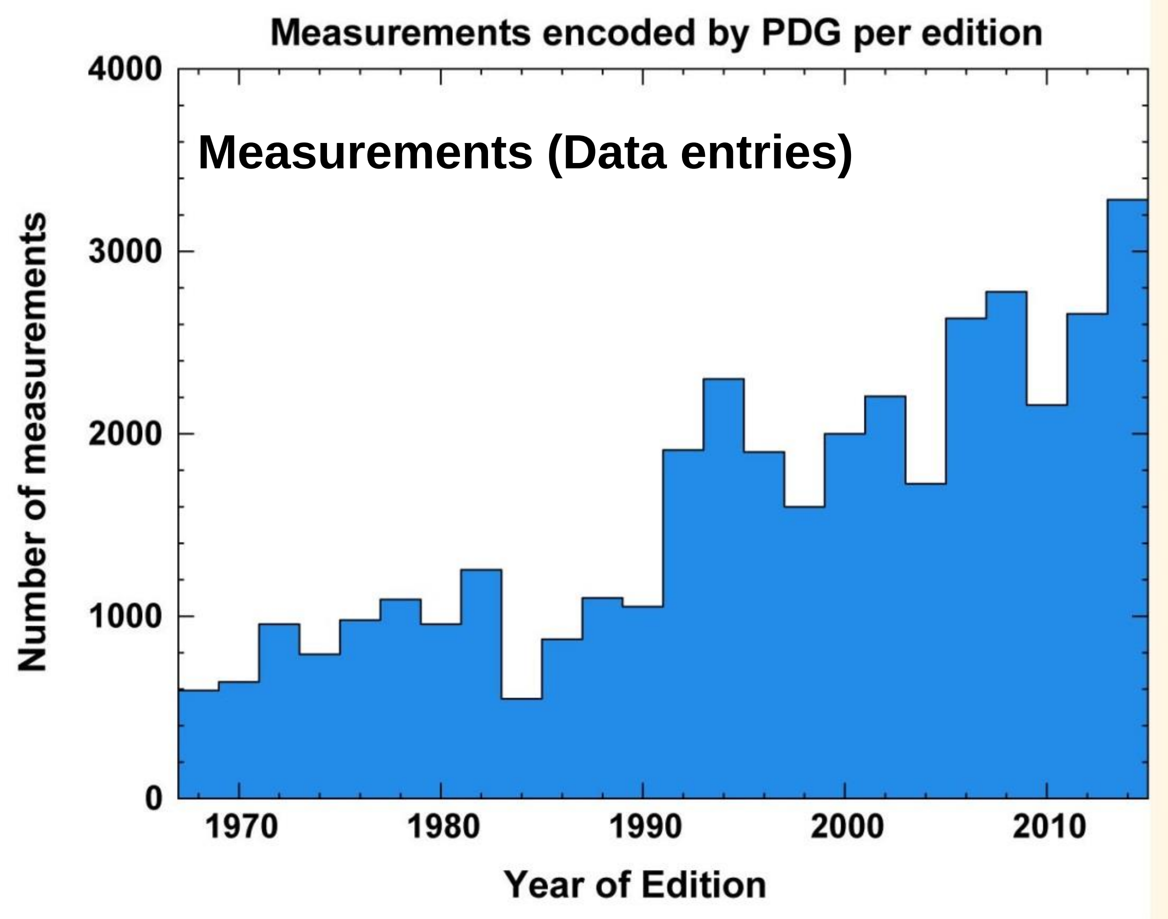
Huge Increase in Search Papers

Year of Book	Number of Search Papers
2010	136
2014	509



Hits per Year on pdgLive Website in 2012-2016
In progress
0.0
0.2
0.4
0.6
0.8
Hits per Year (in Millions)
2012
2013
2014
2015
2016
Year

Workload Trends

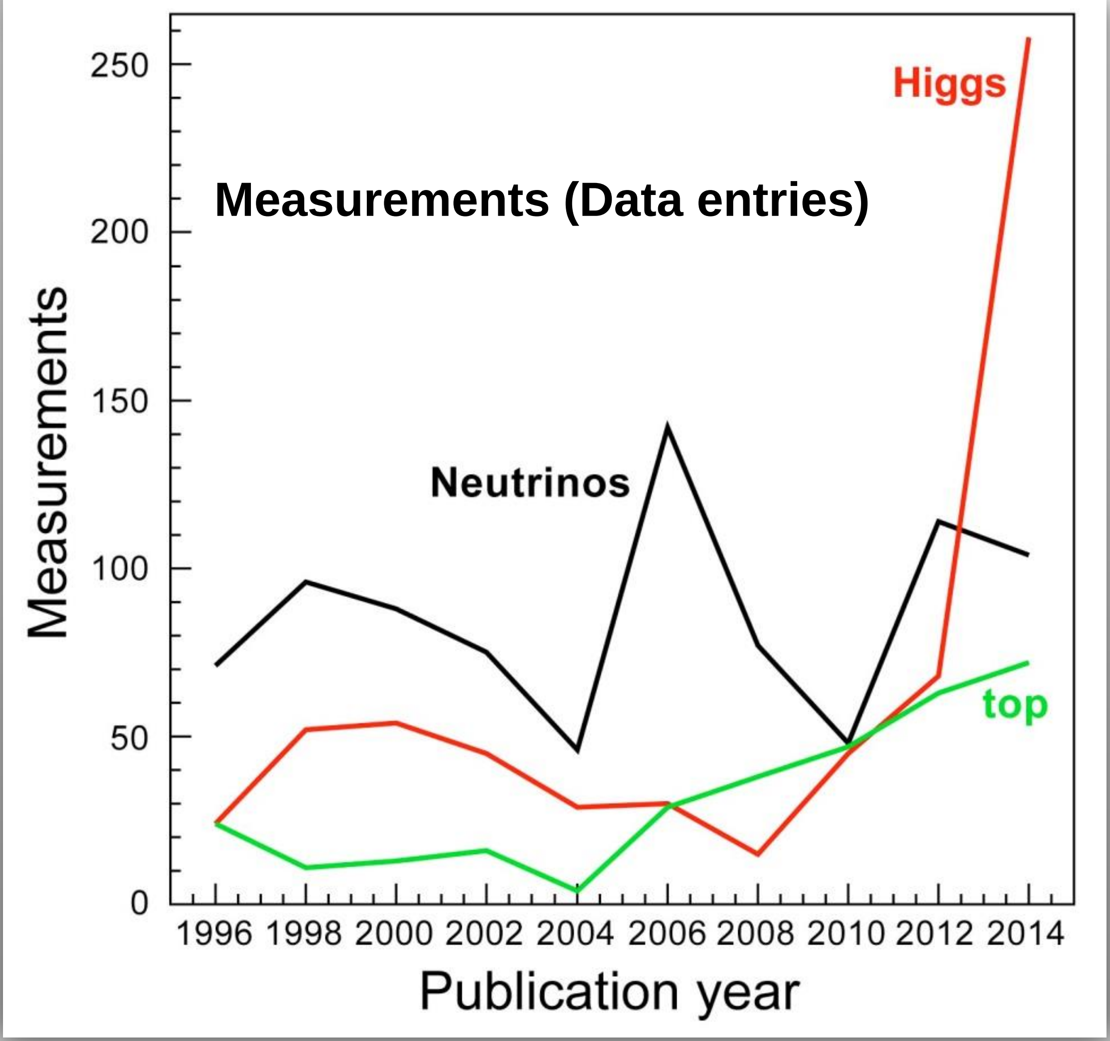


Some editions are more or less than 24 months, yielding fluctuations in graphs.

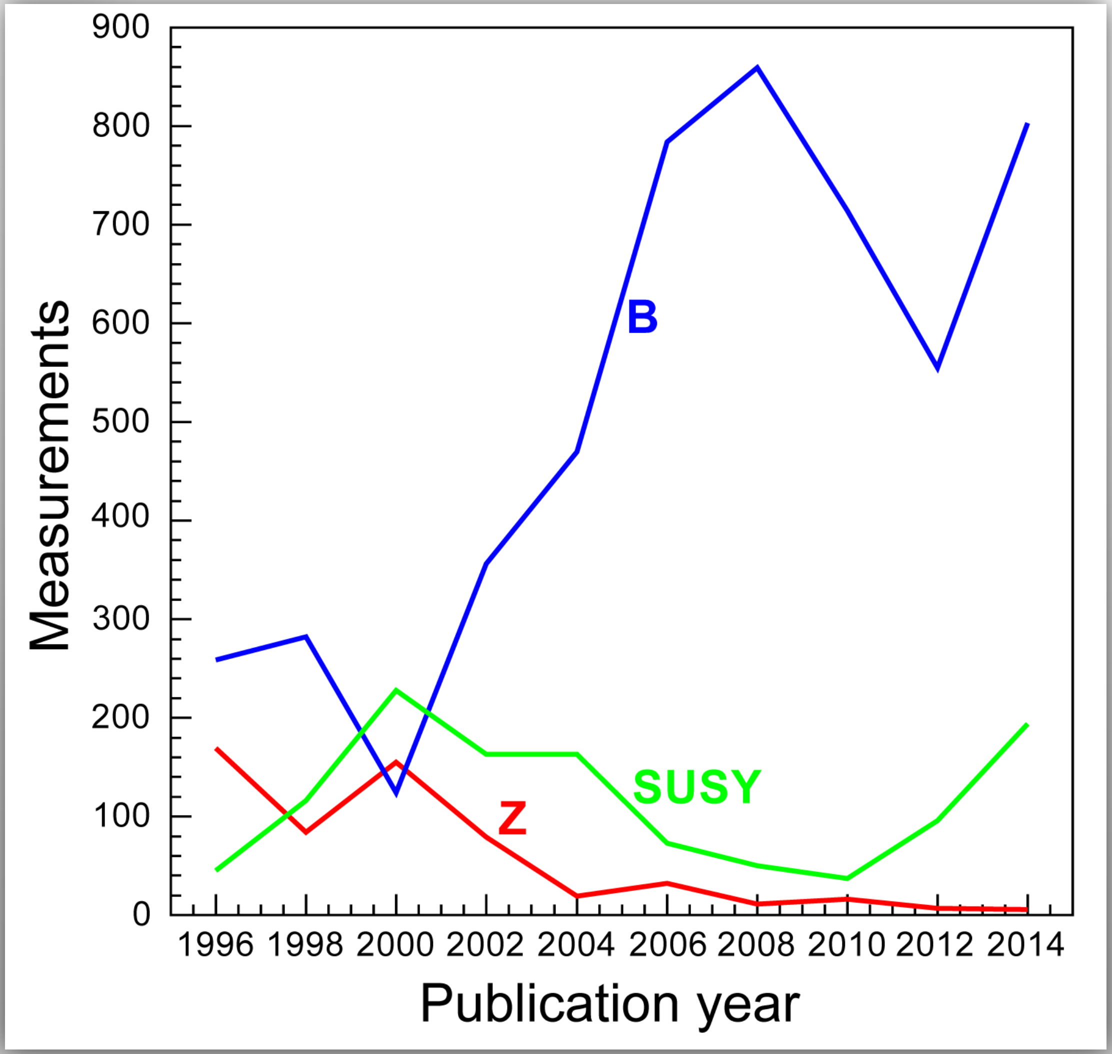
LHC bump

So there is an increasing workload on the LBNL group.

Data versus time

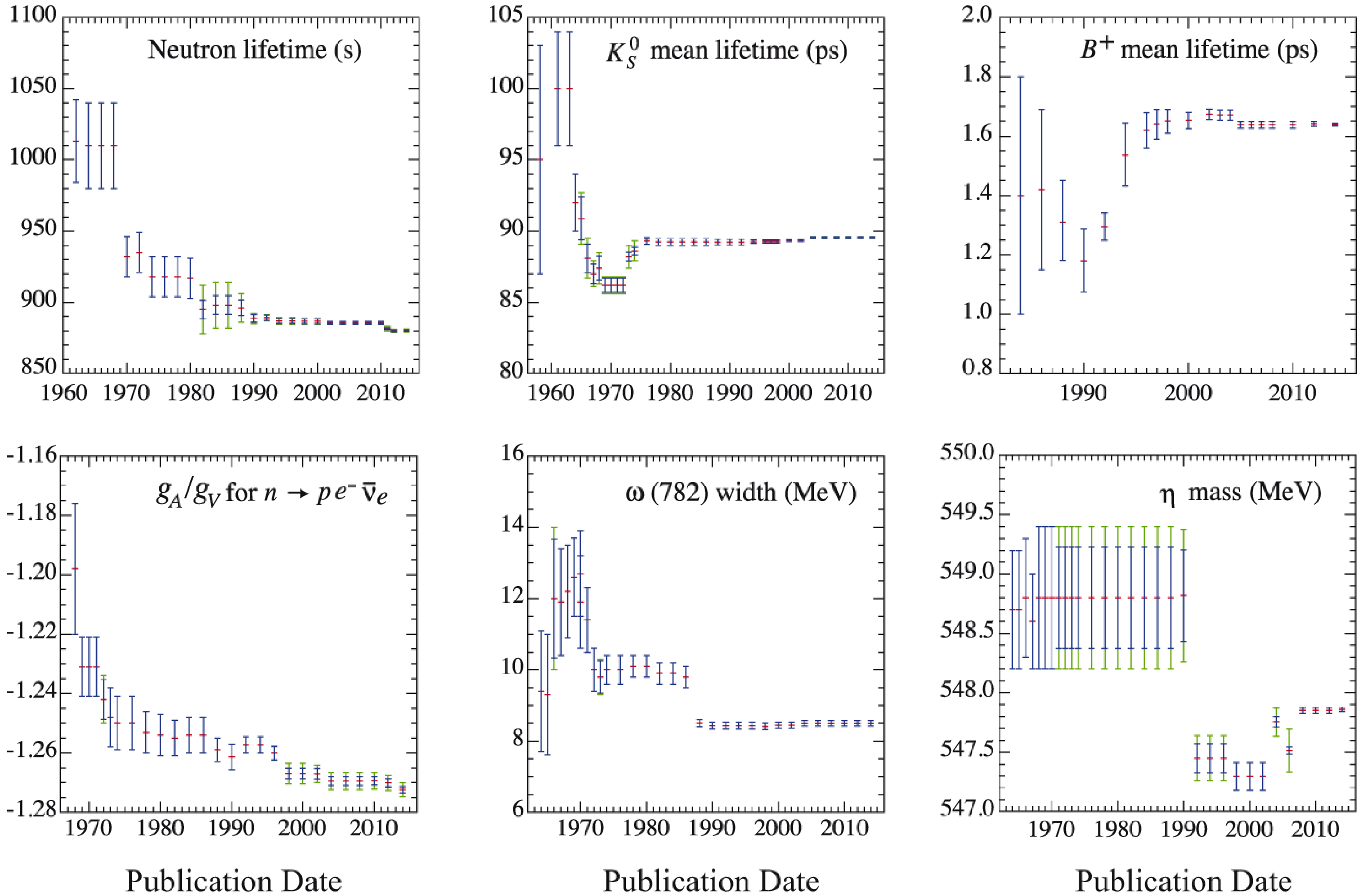


Data versus time



Measurements (Data entries)

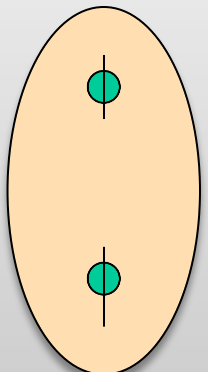
History Plots

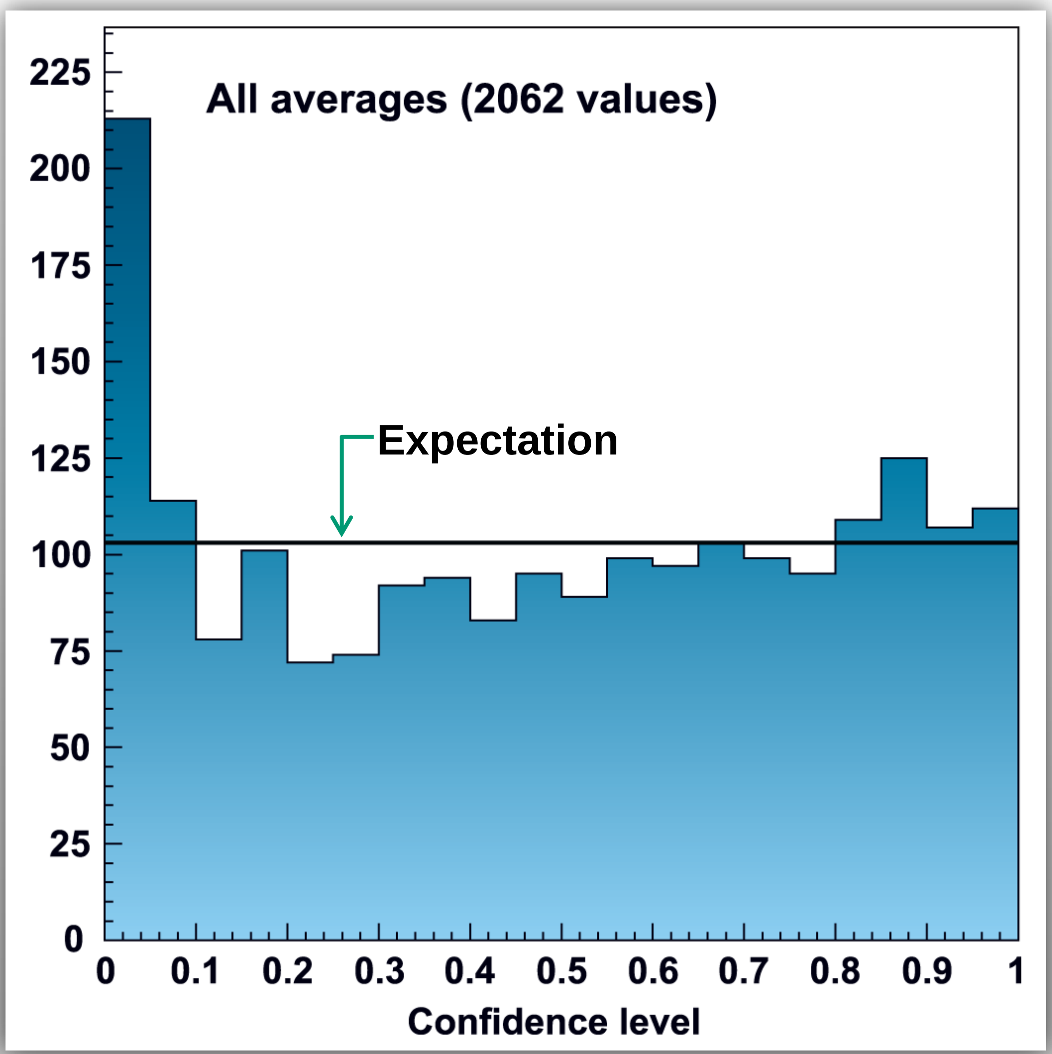


Confidence Levels in PDG Averages

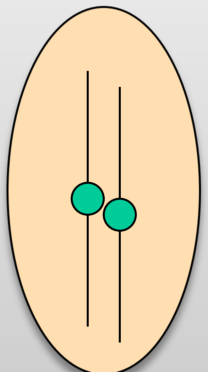
Each point is one average.

Peak at left due to conflicting measurements.



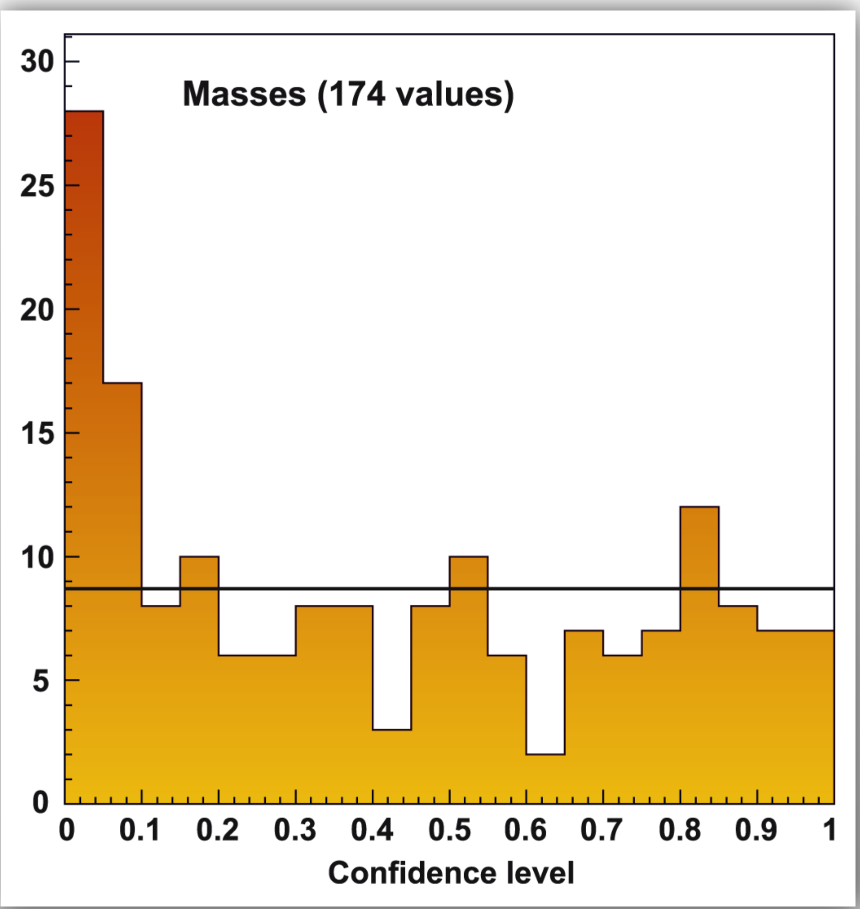


Broad peak at right due to conservative error bars.

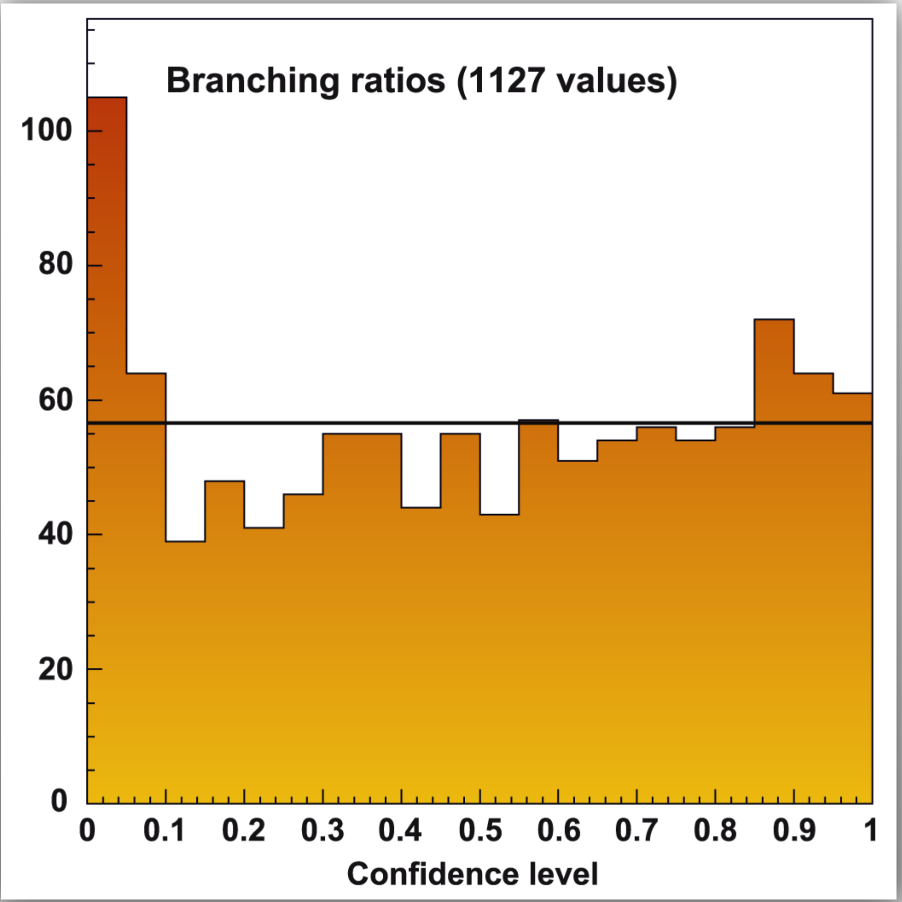


Confidence Levels in PDG Listings

Masses



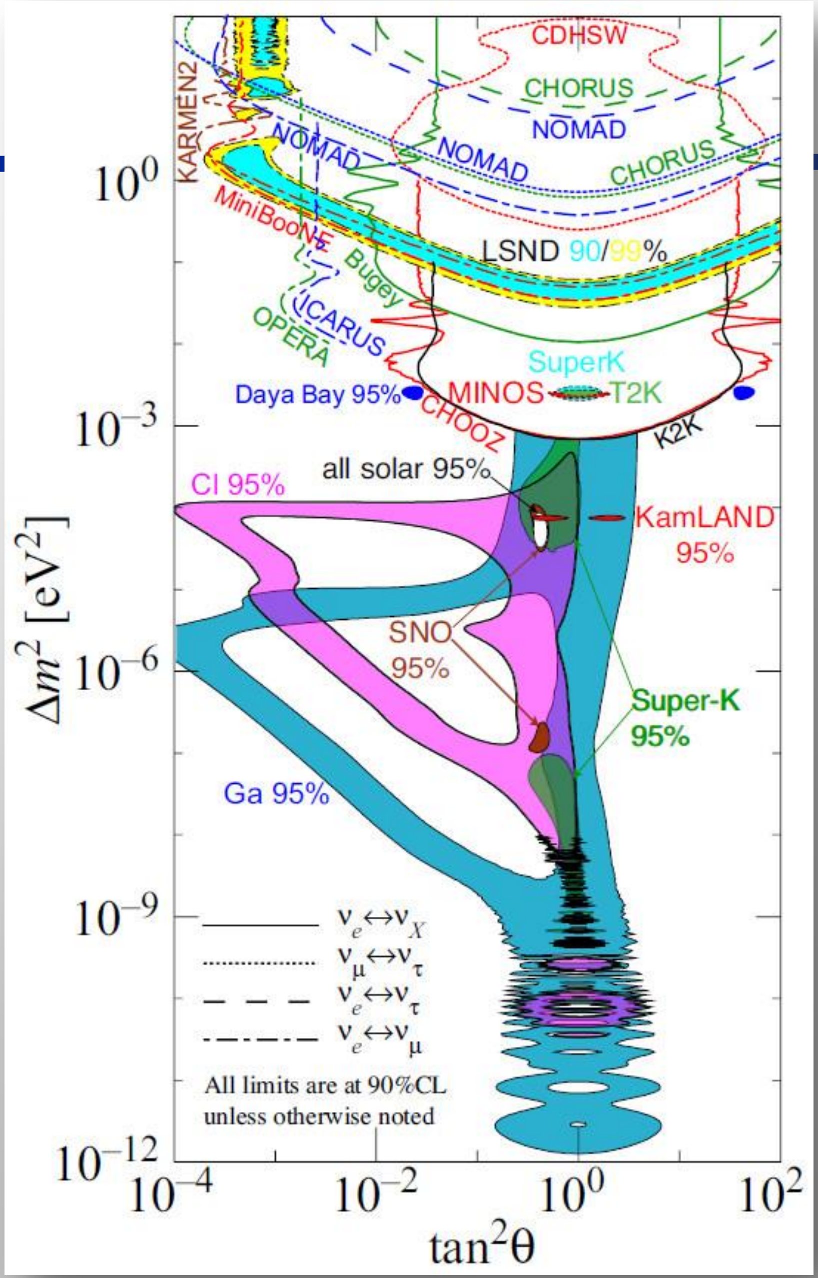
Branching Ratios



About Reviews

Neutrinos

Latest plot shows large mixing of neutrinos



Hitoshi Murayama

112 reviews in 2014 Edition
(most are revised or new)

New reviews on:

- Higgs Boson Physics
- Dark Energy
- Monte Carlo Neutrino Generators
- Resonances

Significant update/revision to reviews on:

- Top Quark
- Dynamical Electroweak Symmetry Breaking
- Astrophysical Constants
- Dark Matter
- Big Bang Nucleosynthesis
- Neutrino Cross Section Measurements
- Accelerator Physics of Colliders
- High Energy Collider Parameters

New in 2016 Edition:

- Inflation
- Grand Unified Theories
- Pentaquarks
- etc.

PDG Advisory Committee

"The PDG is already operating at a very efficient level, which is how they have managed to expand the coverage into the field of cosmology and particle astrophysics while still maintaining the high standards in the rest of particle physics.

"This efficiency comes from several advances:

- **the new software infrastructure that allows for more authors to enter data themselves,**
- **the fact that the PDG works in concert with experimental working groups when appropriate, and**
- **the fact that the PDG has been able to coax some 200 authors to contribute and a total of 700 physicists worldwide to provide input through the peer review process.**

"The quality of the work that the PDG represents is part of what makes people want to provide input to the PDG process."

Quotes

- “Several reviewers remarked that HEP would be a qualitatively weaker field if the PDG were not there as a current, growing resource.”

  DOE S&T review of LBNL

- “This review is used by people at all levels in the both theory and experiment, and the committee frankly cannot imagine the field without the compilation that is embodied in the RPP.

  “The importance of this work can not be overstated.”

  PDG Advisory Committee

Reviews: Linked or Not to Listings

616,000 downloads of Reviews per year.

Linked Reviews:

2/3 of reviews are linked to the Listings

(Higgs, neutrinos, top quarks, K mesons, B mesons, SUSY, etc.).

Vital to understanding content of Listings.

Non-linked Reviews:

The 1/3 non-linked reviews are both vital and among the most downloaded.

(Electroweak Model, Statistics, Particle Detectors, Cosmological Parameters, etc.)

Astrophysics & Cosmology

Downloads of Reviews:

Astrophysical Constants 6091

Big Bang Cosmology 7799

Cosmological Parameters: H_0, Λ, Ω, etc. 13769

Experimental Tests of Gravitational Theory 4234

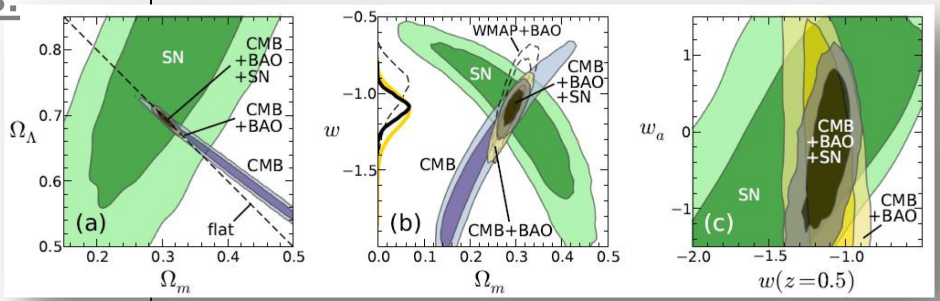
Dark Matter 8591

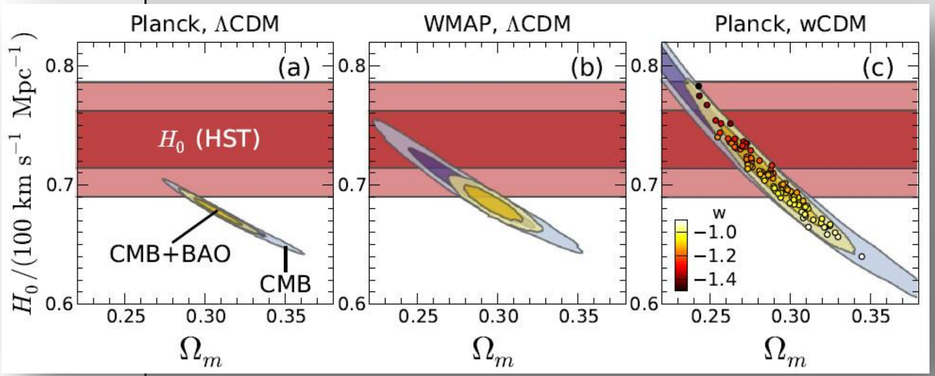
Dark Energy 7627

Cosmic Background Rad. 5587

Big Bang Nucleosynthesis 4343

Total Cosmology Downloads 58,041 (9.4%)





(from Dark Energy review)

What is the PDG Collaboration?

PDG at LBNL (Central coordination, data evaluation, quality assurance, schedule control, and production)

3.5 FTE's (6 physicists: half research) + editor, programmer, etc.

PDG Collaborators outside of LBNL PDG

200 Physicists from 24 countries (volunteers at <5% level).

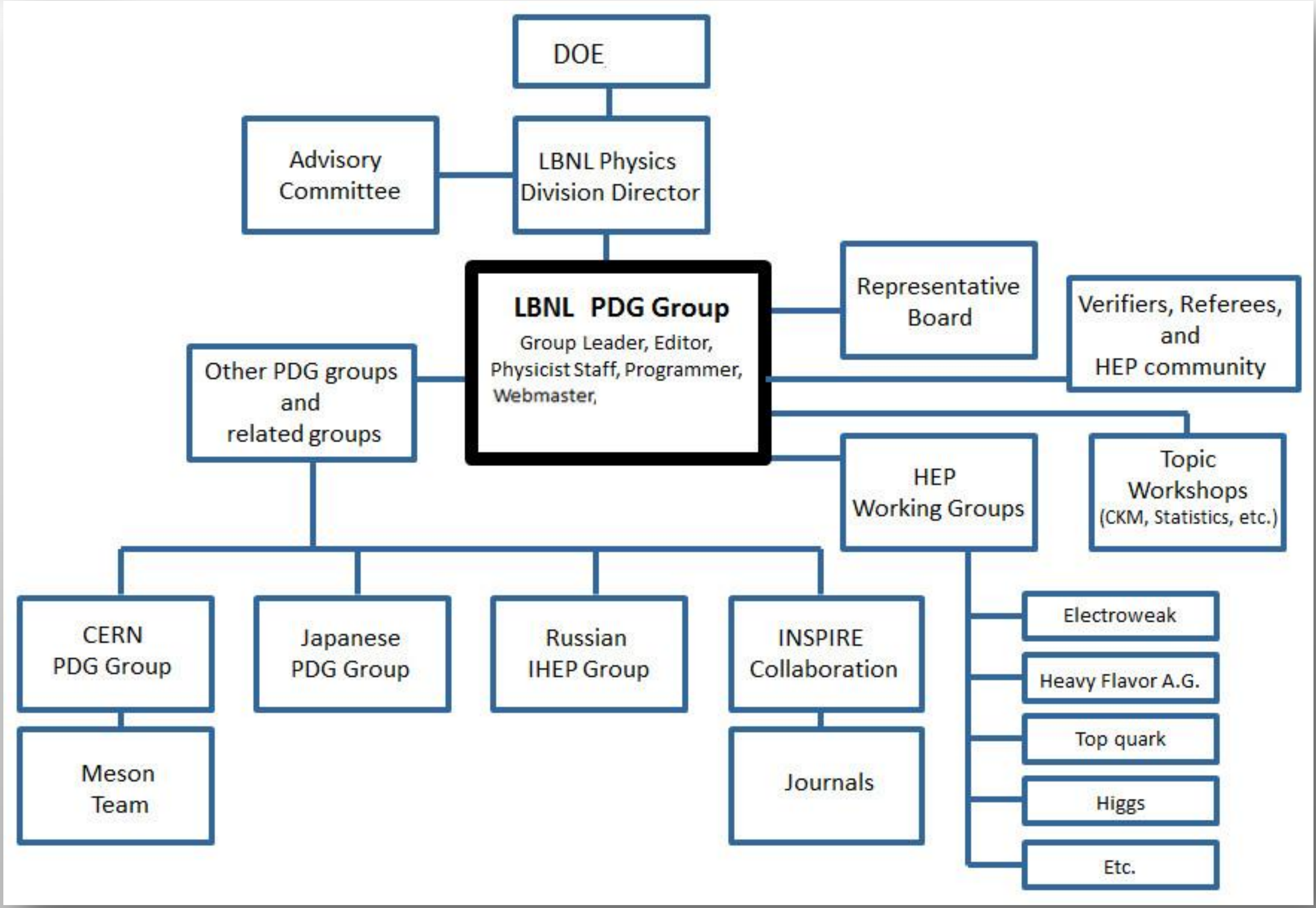
PDG Consultants – 700 physicists

- **Experiments' Physics Coordinators (etc.) – verifying data listings**
- **Referees of reviews (3-5 for each review)**
- **General consultants on content**

PDG Users: tens of thousands

Clearly this cannot work without vital central coordination.

PDG Chart
(much to coordinate)



M. Barnett – May 17, 2017

Central Leadership

PDG leadership group at LBNL coordinates the entire effort

- Produce and publish the Review (book, booklet, web, pdgLive)
- Data evaluation, all the final checking & editing
- Major contributor to the content
- Choose the authors and the content
- Maintain & drive the schedule
- Coordinate the input of 700 consultants from HEP community

Essential for

- High quality
- Timely publication